

JPL Publication 06-5, Rev A



Earth-Like Exoplanets: The Science of NASA's Navigator Program

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October 16, 2006

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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Abstract

This book outlines the exoplanet science content of NASA's Navigator Program, and it identifies the exoplanet research priorities. The goal of Navigator Program missions is to detect and characterize Earth-like planets in the habitable zone of nearby stars and to search for signs of life on those planets.


The Navigator Program includes the ground-based Keck Interferometer and the Large Binocular Telescope Interferometer, designed to measure the inner and outer dust disks of nearby stars. The Navigator Program also includes three space-based missions: Space Interferometry Mission (SIM) PlanetQuest, Terrestrial Planet Finder Coronagraph (TPF-C), and Terrestrial Planet Finder Interferometer (TPF-I). The scientific goals of these missions are complementary: SIM will determine the orbits and masses of nearby planets, down to about one Earth-mass; TPF-C and TPF-I will detect Earth-like planets in the habitable zone of nearby stars and will measure the colors and spectra of these planets, in the visible and infrared respectively, to characterize them and look for signs of life. Each mission measures unique properties of exoplanets. Together the missions build a synergistic picture of exoplanets. No single mission can do this.

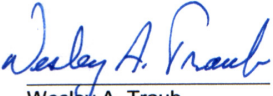
We describe expected progress in exoplanet science research. We highlight areas worthy of investment by NASA. We list opportunities for funding from NASA and other agencies.

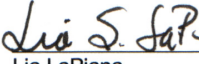
This book also serves a programmatic purpose. The science priorities described here are tied to the development phases of individual Navigator missions. Preparatory science conducted by observational and theoretical research is essential to help define future missions, to aid our understanding of the planets that could be discovered, and to better understand the star systems that these missions will study. The programmatic gates and preparatory science requirements are listed for SIM PlanetQuest, TPF-C, and TPF-I.

We will annually review and update this book as needed. The current edition is available online at <http://planetquest.jpl.nasa.gov/documents/NavigatorScience2006.pdf>.


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Preface

Our understanding of planetary systems has undergone a profound shift since 1995 when the first exoplanets were discovered. The field has been transformed from one in which extrapolation from our own Solar System has been replaced by the empirical wealth of over 200 exoplanets. The sheer variety of giant planets and planetary systems—including planets orbiting very close to the stars or on highly elliptical orbits, and resonance-locked pairs of planets—has come as a surprise. Yet these discoveries just reveal the tip of the iceberg. If our Solar System is typical, then these giant planets may be accompanied by many sibling terrestrial planets.

The Navigator Program is the focus of NASA's efforts to enable advanced telescope searches for Earth-like planets. The objectives of the Navigator Program are simply stated:

- To search for and detect terrestrial planets that might exist in the habitable zones of nearby stars.
- To characterize the atmospheres of all detected planets.
- To search for indicators of the presence of life on terrestrial planets.
- To study each planetary system (planets plus zodiacal dust) as a whole.

To meet these objectives, the Navigator Program requires preparatory science activities for a variety of reasons: to provide the astronomical information needed to assist in decisions concerning the architecture of its missions; to specify the most promising spectral markers for characterizing planets and detecting signs of life; to determine the volume of space that will be searched; and to characterize target stars. In addition, NASA and the Navigator Program must ensure that a robust science community with a broad scientific understanding of the formation and evolution of planetary systems is prepared to plan and interpret observations from future Navigator missions.

This book was written by scientists selected for their expertise in each area. The chapters were first presented and debated at a Navigator Program Science Forum meeting held on 8–9 May 2006 at the United States Naval Observatory in Washington, D.C. About 70 scientists participated in this forum, with additional attendees from the Navigator Program and NASA Headquarters. A four-person independent review board also attended and provided critical oversight guidance on the content of this report.

This volume was preceded by *Precursor Science for the Terrestrial Planet Finder* (Jet Propulsion Laboratory, Pasadena, CA, October 2004). The exoplanet field is changing rapidly, so that now, two years later, you have in your hand a much-updated and re-titled report, *Earth-Like Exoplanets: The Science of NASA's Navigator Program*. We plan to update this volume every year or two, as needed.

1 Introduction

1.1 Exoplanet Science: A New Interdisciplinary Field

One of the most fundamental and provocative questions that can be asked is whether life exists outside of our Solar System. This question has remained a philosophical one for at least 2300 years. It is now, however, practical and feasible to seek the answer from a scientific perspective. A clear path toward answering whether we are alone in the Universe exists, and following it is the purpose of NASA's Navigator Program. This path involves a multidisciplinary suite of research efforts, centered on finding and characterizing exoplanets that could harbor biological activity similar to terrestrial life.

Along the path to finding life similar to that on Earth, we will explore a spectrum of worlds (perhaps broader than we can now imagine) and unravel the puzzles of planet formation, evolution, and diversity, as well as the extent of the planetary population, which could conceivably outnumber the stars. Part of the wealth of this new field is the fact that planets are extremely diverse as compared to stars. The Vogt-Russell theorem* states that the properties of a star are fully determined by the mass and chemical composition. The thermodynamic-equilibrium premise of this theorem has been applied to many other areas of astrophysics, but a cursory examination of the planets of our Solar System and their moons shows that planets of similar mass (whether they be "rocky" or gaseous giants) can have vastly different salient characteristics. This means that a full understanding of planets in general requires a working knowledge of diverse fields, including star formation, orbital mechanics, geology, geophysics, climatology, aeronomy, chemistry, biology, and various engineering disciplines.

1.2 The State of Exoplanet Science

Nearly all of the 200-plus known exoplanets have been found within the past 11 years. Of these, 94% were discovered using the radial-velocity technique, 3% by transit photometry, 2% by gravitational microlensing, 2% by direct imaging, and 2% by pulsar timing. There are about 62 ground-based and 16 space-based search programs, ongoing and future. Over the past half-decade, the discovery rate has been

* H. Vogt, "Die beziehung zwischen den massen und den absoluten leuchtkraften der Stern," *Astron. Nachr.* **226**, 301–304 (1926); H. N. Russell, in *Astronomy*, by H. N. Russell, R. S. Dugan, and J. Q. Stewart, Vol. II: Astrophysics and Stellar Astronomy, p. 910 (Ginn and Co., Boston, MA, 1927).

steady at about 30 exoplanets per year. The rate of discovery seems to be limited mainly by instrumental sensitivity, not the available number of exoplanets.

What do we know about these exoplanets? About 15% of them reside in multiple-planet systems, providing hope that we may someday find analogs to the Solar System. Some other basic statistics are as follows.

The median planet mass is about $1.5 M_J$ (Jupiter masses), or about $450 M_E$ (Earth masses). This relatively large value is almost certainly a result of instrumental detection bias. As discussed in this volume, there are several reasons to expect that many more small planets exist, and will be detected once the newer more sensitive techniques are employed.

The median semi-major axis is about 0.8 astronomical units (AU), partly reflecting an instrumental bias toward smaller values, but also showing that these giant planets mostly exist much closer to their parent star than would be expected from Solar System experience. The inference is that they have migrated from greater distances, which in turn raises many questions about what started and stopped the migration, what happened to planets that were in the migration path, and whether the stars without such migrated planets in fact have terrestrial planets instead.

The median distance of these planets is about 36 parsecs (pc), so there are many nearby stars with planets. This value is limited by the faintness of more distant stars, and not the intrinsic supply of planets.[†]

What do we *not* know about these exoplanets? The answer is, “almost everything,” and that is the main reason we have the Navigator Program, to find out all the missing pieces of the puzzle. Here are some of the things we do not know, but which could be discovered through Navigator Program and related missions.

We do *not* know the strength of the exozodiacal background intensity in typical stellar systems. This is important from the point of view of planet detection because, in the ideal case, this background would be small compared to the planet.

We do *not* know the fraction of stars (η_{planets}) that have planets of any kind, small or large. Given the ubiquity of massive planets found to date, and the fact that every star was formed from a flattened disk of gas and dust, it is possible that the value of η_{planets} is close to unity. What is needed is a comprehensive planet-search program that has a high yield (for good statistics) and known biases (so accurate correction is possible). The Kepler (NASA), COROT (European Space Agency [ESA]), and SIM-PlanetQuest (NASA) missions will each contribute answers to this question, as discussed later in this book.

We do *not* know the shape of the exoplanet mass distribution function $dN/dm = \xi(m)$, although over the range of planets detected thus far, the shape of this function increases steeply toward small masses, with $\xi \sim 1/m^{1.1}$. By comparison, the shape of the stellar mass function, $dN/dM = \xi(M) \sim 1/M^{1.3}$ for the majority (77%) of stars, is also steeply increasing toward small masses (here M dwarfs with masses less than 0.5 suns).[‡]

[†] <http://exoplanet.eu> (see *Interactive Catalog*, then *All Candidates Detected*, and *Histograms*).

[‡] *Allen's Astrophysical Quantities*, 4th Edition, A. N. Cox, editor, pp. 488–489, AIP Press, Springer-Verlag, New York, NY, 2000.

We do *not* know the average density of most exoplanets, save for those that happen to transit their star. Density is obviously important because it separates rock-like from gas-like planets. For the majority of planets we need direct detection to estimate diameter which, with mass, gives density.

We do *not* know the fraction of stars that have terrestrial planets in the habitable zone, usually called somewhat loosely η_{\oplus} . Here by “terrestrial planet” we mean “a planet which is primarily supported from gravitational collapse through Coulomb pressure, and which has a surface defined by the radial extent of the liquid or solid interior.” And a “habitable planet” is “a terrestrial planet on whose surface liquid water can exist in steady state.” The mass of a habitable planet is expected to lie in the range from about 0.5 to 10 Earth masses, limited by atmospheric escape (hence no liquid water) at the low end, and the accumulation of a very massive atmosphere (hence no detectable surface) at the high end. Some arguments suggest that η_{\oplus} is on the order of 0.1, but given the possible steepness of the mass distribution function, it may be that η_{\oplus} is actually much larger. (Further explanations and definitions of frequently used terms are given in Appendix B.)

We do *not* know anything about the colors or spectra of the vast majority of exoplanets, in the visible or infrared. Tantalizing hints of atmospheric composition can be gleaned from transit and eclipse spectra, but these are rare events. There are theoretical predictions of the expected colors and spectra of gas giant, ice giant, and terrestrial planets, under a variety of circumstances of distance from star, age, etc.; and we also have the Solar System examples to guide us, but as yet there is no body of observational data on which to test these theoretical models.

We do *not* know anything about the atmospheres, clouds, surfaces, and variability of these quantities for the known set of exoplanets, and of course for those yet to be found, including terrestrial planets.

We do *not* know anything about the habitability or signs of life on any exoplanet, or if there are any Earth-like exoplanets.

Simply stated, we need to find answers to all of the above questions. These answers will come from observations using existing and planned ground-based and space-based observatories, as well as balloon-borne and lunar-based observatories, in combination with theoretical studies. Some of these observatories, such as Spitzer and the James Webb Space Telescope (JWST), are already operational or under construction. Others, including TPF-C and TPF-I, are still in the pre-planning stages. The preparatory science needed for these new observatories is a major theme of this book.

Exoplanet science and technology are the heart of the Navigator Program at NASA. Key objectives for preparatory science in the Navigator Program are as follows:

1. To estimate the fraction of stars with terrestrial-sized, potentially habitable planets. This knowledge helps ensure that missions to characterize terrestrial planets are correctly sized.
2. To determine the prevalence of dust disks around other stars and how it will influence the mission designs. Exozodiacal dust may serve as a signpost for the presence of planets, and yet may also degrade the ability of a Navigator mission to detect planets.
3. To study potential target star systems in terms of science impact, technology implications, and mission operations.

4. To determine the biomarkers and other observable properties of habitable Earth-like planets that will drive the design of missions to characterize terrestrial planets. There is broad agreement that visible and mid-infrared observations provide powerful diagnostics of habitability and even of life itself. The interpretation of planetary spectra is the key to characterizing any planets that are detected.
5. To build community infrastructure, including data archives, fellowship programs, and research opportunities centered on Navigator Program science. A vigorous program of theoretical and observational investigations is vital to building a cadre of scientists ready to exploit observations of exoplanets.
6. To plan for the types of general astrophysics observations that might be carried out in addition to the prime science of detecting and characterizing Earth-like exoplanets. As an example, it is possible that the large telescope needed for TPF-C could also be useful to carry out some or all of the Joint Dark Energy Mission (JDEM) observations. A nominal 50–50 split of time between exoplanet science and general astrophysics is envisioned with each mission in the Navigator Program.

For each key objective there is a chapter in this volume that discusses the present state of the science and suggests areas where research is needed.

1.3 References

NASA and ESA have had planet-finding in their core strategic plans for many years. The references listed here are mostly from NASA and National Research Council (NRC) roadmaps, or the equivalent, from the past 10 years. The reference dated January 2004 is a presidential directive to NASA. But the strategic interest goes back much farther; for example, planet-finding was one of the original goals proposed for the Hubble Space Telescope (HST) by Lyman Spitzer in 1962.[§]

Today we have the advantage of knowing that there are literally hundreds, probably thousands, of planets within our astrophysical reach. We possess the technical means of studying these planets with telescopes, coronagraphs, and interferometers. This is why the strategic plans listed here have even more relevance now than when some of them were originally conceived. We invite the reader to sample these web sites to see the fervor with which many of the authors looked forward to detecting and characterizing exoplanets and searching for signs of life.

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[§] Lyman Spitzer, “The Beginnings and Future of Space Astronomy,” *American Scientist* 50, 473–484 (1962).

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2 NASA Missions and the Search for Earth-Like Planets^{**}

This chapter describes the science strategy and the contributions from missions directly related to the search for habitable worlds. Over the next two decades, NASA will launch a series of spaceborne telescopes that will build on one another's achievements to address the goals of finding Earth-like planets around other stars and examining those planets for signs of life. This program directly supports *A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration* (2004), which calls for "advanced telescope searches for Earthlike planets and habitable environments around other stars" as one of the foundations of NASA's exploration goals. The missions mentioned in this chapter include the NASA missions Spitzer, SOFIA, Herschel, James Webb Space Telescope (JWST), and Kepler. However, particular emphasis is given to NASA's missions within the Navigator Program: Keck Interferometer (KI), Large Binocular Telescope Interferometer (LBTI), Space Interferometry Mission (SIM) PlanetQuest, TPF-C, TPF-I, and Life Finder.

2.1 Fundamental Questions

Toward the ultimate goal of finding life on other planets, we will address these questions:

1. How do planetary systems form and evolve?
2. Are there other planetary systems like our own?
3. Is there life elsewhere in the Universe?

The search for habitable worlds begins with an understanding of the formation of planetary systems in protoplanetary disks to learn how planetary systems form, around which types of stars planets form, how often planets form, and how the disk properties affect the distribution of final planet sizes and orbits. The formation and dynamical evolution of gas-giant planets are also important because their gravitational

^{**} The text of this chapter was originally written to be included as Chapter 4 "Exploring New Worlds" in *Science Program for NASA's Astronomy and Physics Division 2006*, edited for the NASA Science Mission Directorate by Adam Burrows (University of Arizona) and Kathryn Flanagan (Massachusetts Institute of Technology). Minor changes to the text have brought the material up to date from the original version published in July 2006. The source document is the first cited reference in the previous chapter.

Table 1. Contributions of NASA Missions to the Search for Earth-like Planets

Exploring New Worlds													
OBJECTIVE 1	R&A	HST	Spitzer	SOFIA	Herschel	JWST	KI	LEI	Kepler	SIM	TPF-C	TPF-I	LF
Study the formation and evolution of planetary systems													
Study the formation and structure of debris disks in young planetary systems.	✓	✓	✓	✓	✓	✓	✓	✓					✓
Investigate the properties of young gas-giant planets around other stars.	✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	
Understand the creation and delivery of organics to planets.	✓		✓	✓	✓	✓						✓	
OBJECTIVE 2													
Explore the diversity of other worlds													
Study the architectures and evolution of other planetary systems.	✓								✓	✓	✓		
Investigate the frequency of giant planets around other stars.	✓						✓	✓	✓	✓	✓	✓	
Understand the frequency of Earth-sized planets.	✓								✓	✓	✓	✓	
OBJECTIVE 3													
Search for habitable planets and life													
Investigate the properties of gas-giant planets in habitable systems.	✓					✓			✓	✓	✓	✓	
Characterize the properties of terrestrial planets around other stars.	✓											✓	✓
Investigate the biosignatures of other worlds.	✓											✓	✓

influence plays a crucial role in the formation of smaller worlds, in the stability of their orbits, and in controlling the delivery of organic-rich material into an inner planetary system.

The technology required to detect and characterize potentially habitable worlds is enormously challenging, and no single mission can provide all the measurement capabilities. Nor can any one mission be as productive operating alone when compared with its power working as part of a carefully planned program. To understand whether life is common or rare in the universe, we must meet the technological challenges and embark on a series of complementary and interlocking explorations, each activity supporting and extending our efforts to characterize planetary systems and search for terrestrial planets and life. The key NASA missions that are central to planet finding are highlighted later in this chapter.

The sections in this chapter describe the science and missions needed to answer the three fundamental questions stated above. The science objectives and associated missions are also summarized in Table 1. The chapters that follow then describe the precursor science activities that will lay the groundwork for future exoplanet studies, with emphasis on missions in the Navigator Program. Linking the missions together will be precursor observations with a variety of space-based and ground-based telescopes, as well as a rich program of research and analysis, laboratory astrophysics, and theoretical investigations supported by the Research & Analysis program, including the TPF Foundation Science program, Michelson Science Fellowships, and the NASA Astrobiology Institute.

2.2 Study the Formation and Evolution of Planetary Systems

To learn how common (or rare) planetary systems like our own are, we need to understand the evolution and nature of existing planetary systems. The seeds of future planets are sown and nurtured in the protoplanetary disks. Many fundamental questions remain about how the final configurations of gas-giant and terrestrial planets arise from these seeds. An ambitious research program of theory and observation will discover the relationships between gas giant and terrestrial planet formation and how the materials necessary for life on terrestrial planets become plentiful.

The flagship mission for observing the formation of planetary systems will be the James Webb Space Telescope (JWST). JWST will probe the earliest moments of star and planet formation. But, JWST will also study planetary debris disks, the remnants of the planet-formation process, to yield new information on the distribution and composition of dust arising from collisions in cometary and asteroid belts. This dust provides the raw material for organic material eventually responsible for making life possible. SIM PlanetQuest will play an important role by carrying out a census of Jupiter-size planets around young stars in the immediate vicinity of the ice-condensation line where such planets are thought to form.

Probe Planet Formation

Ongoing planet formation induces structures in young disks that may be observable with new large telescopes and interferometers. High-spatial-resolution and high-contrast-coronagraphic imaging can reveal ripples and gaps in disks that help locate a perturbing planet and provide estimates of its mass. JWST, as well as the ground-based Keck Interferometer (KI) and Large Binocular Telescope Interferometer (LBTI), will address these observational problems. High-resolution infrared spectroscopy with SOFIA will be able to resolve planet formation within the habitable zone. However, the detection of a gap associated with a proto-Jupiter, located 5 astronomical units (AU) from a star in a nearby star-forming region, will require an angular resolution beyond the capabilities of JWST, but will be well-suited to the TPF Interferometer mission or to spectroscopy with the Single Aperture Far-Infrared Observatory (SAFIR) mission operating in the far-infrared. ALMA will also be able to detect gaps caused by giant planets orbiting near 5 AU in protoplanetary disks, possibly by 2010 or so.

As terrestrial planets grow, small dust grains coagulate into planetesimals that are stirred by the presence of gas giants. The interplay between the rocky planets and their giant siblings will change the structure of asteroid belts around other stars over time.

Comparing the dust signatures from planetesimal debris belts with the presence or absence of planets will reveal this dance. Infrared telescopes (such as SOFIA, JWST, Herschel, and SAFIR) will allow us to determine the evolving location and composition of dust in planet-forming disks.

Detect the Youngest Planets

With sufficiently high spatial resolution, it will be possible to image young planets directly. Adaptive optics imagery from ground-based telescopes and interferometry using KI and LBTI will give us first glimpses of embedded young Jupiters, while JWST's coronagraphs in its near- and mid-infrared cameras may find young Jupiters around nearby young stars (150–500 light-years). JWST's near-infrared camera may possibly even detect directly a handful of old, cold Jupiters around the nearest main sequence stars.

SIM PlanetQuest will be able to find gas-giant planets around young stars (1–100 Myr) in the immediate vicinity of the habitable zone, near where Jupiter and Saturn sit today in our Solar System. Radial velocity detection of planets is impossible in these cases because of photospheric activity and rapid stellar rotation, while imaging searches are limited to planets located tens of astronomical units away from their parent stars. SIM PlanetQuest will survey approximately 2000 stars looking for planets with masses larger than that of Saturn's in orbits from less than 1 AU to beyond 5 AU. SIM will investigate formation scenarios for

giant planets and study migration mechanisms that might explain the puzzling presence of gas-giant planets orbiting mature stars well inside 1 AU.

The TPF-I mission, operating in the mid-infrared, will glimpse deep within dust-enshrouded protoplanetary disks to cleanly separate planets, disk, and star. Together theory and observations will begin to explain the influence of planets like Jupiter on the formation of terrestrial planets.

Understand the Creation and Delivery of Organics to Planets

The next big step in understanding the formation and evolution of habitable planets is to study how terrestrial planets receive and store the materials they need to foster life. Research has shown that organic molecules, the building blocks of life, likely permeate the universe, but their identities, abundances, and distribution still need to be understood in our own and other galaxies. Planets like Earth formed too close to the Sun to keep their initial water content. Planetesimals, the building blocks for planets that formed in the gas-giant region, provided a reservoir for water and other volatiles necessary for terrestrial life. The organic content of the material left over in the debris disk phase depends largely on the extent of processing during the gas-rich disk phase. The compounds frozen onto rocky bodies when the disk clears provide most of the carbon that will be available to developing planets, but delivery of volatiles and organics by small planetary system bodies will continue throughout a planet's history. Observations of ice and organic compounds in disks with JWST, TPF-C, TPF-I, SAFIR, and other future missions with spectroscopic capability can be combined with theories of organic chemistry, volatile processing, and orbital dynamics to place constraints on the formation and evolution of prebiotic compounds and their delivery to terrestrial planets.

2.3 Explore the Diversity of Other Worlds

Although we will learn about the formation of planetary systems from studying the very youngest stars, an exploration of older systems will help us better understand our own Solar System and provide us with clues to its ultimate fate. Our solar neighborhood includes stars that span ages from stellar birth to twice as old as the Sun, and studies of any planetary systems around these stars will allow us to better understand how planetary systems evolve over time. A broad census of planetary systems will also form the observational foundation for our understanding of how common planetary systems are and the diversity of their architectures.

A comprehensive census of the planetary systems in our solar neighborhood (using ground-based observations and observations from Spitzer, SOFIA, Herschel, JWST, SIM PlanetQuest, TPF-C, and TPF-I) will enable investigation of the relationship between all the main components of a planetary system, gas-giant and rocky planets, cometary systems (Kuiper belts), and asteroid belts (zodiacal clouds). Kepler will find correlations between the presence of Earth-like planets and both stellar characteristics and the presence and orbits of giant planets. These studies will set the stage for follow-up observations to understand the properties of the planets that we find and allow us to understand the larger context of our own planetary system.

No single instrument or technique is capable of finding all planetary system components around stars of all ages. Instead, our understanding of other planetary systems will be achieved with an integrated suite of

ground- and space-based missions that will use complementary instrumentation and techniques to explore the majority of planetary-discovery-phase space. Four fundamental techniques will be used to determine the architecture of planetary systems: radial velocity measurements, transit observations, astrometry, and direct detection. The breadth of discovery space is broad, and the combination of these techniques promises to provide a complete census of Earth-size and giant planets.

Giant Planets: Signposts of a Planetary system

Giant planets, which are unlikely to harbor life, dynamically constrain the orbits available for terrestrial planets. Giant planets are the older siblings — both the bullies and protectors of the terrestrial planets. How they stir up the disk determines how many comets and asteroids survive to bombard smaller worlds with either sterilizing intensity or with lesser intensity providing life-bringing chemicals. Giant planets in eccentric orbits are less likely to allow terrestrial planets to orbit stably in the habitable zone. However, gas giants might be necessary for shielding terrestrials from life-damaging impacts of comets.

One of the exciting and unexpected results of the planet searches to date is the discovery of large numbers of systems unlike our own. Gas-giant planets have been found to orbit much closer to their stars than Mercury orbits about the Sun. Among the unsolved problems in planet formation today is not just how to form giants, but how to move them to their present locations. Some appear to have migrated large distances while others, such as Jupiter, appear to have mainly remained in place. Many gas giants also have substantial eccentricities — varying the distance from their stars over their orbits. However, these systems exist only for a minority (10 to 20%) of stars, leaving open the possibility that many stars have planetary systems more like our own. About 180 planetary systems (over 200 planets) have now been discovered through ground-based observations. Despite such success, our knowledge of other planetary systems is still very rudimentary. Most planets have been discovered with the radial-velocity technique, which infers the presence of a planet based on its gravitational pull on the parent star. However, the sensitivity of the radial-velocity technique is currently limited to planets of about 7 Earth-masses, and it preferentially detects planets orbiting close to their parent stars. Only 20 exoplanetary systems have more than one detected planet. These planets have been, almost without exception, giant planets that lie closer to their parent star than the giant planets in our own Solar System.

Space-based observations of giant planets with SIM PlanetQuest will provide detailed information on the eccentricity and inclinations of the planetary orbits for planets within 5 AU of their parent stars. This will be our best tool for disentangling the dynamics of systems with multiple giant planets. TPF-C and TPF-I will also be capable of detecting giant planets. Spectroscopy of giant planets with TPF-C and TPF-I will be of particular importance in understanding the chemical composition, physical structure, and overall evolution of these objects. With TPF-C and TPF-I, we will have a sample of hundreds of planets to compare and contrast to one another.

Understand the Frequency of Earth-Size Planets

Although current observations suggest that Earth-size rocky planets *may* be common, their abundance is quite uncertain. The information to date, however, is encouraging:

- Roughly 7% of all nearby stars harbor a giant planet within 3 AU.
- The number of planets increases as mass decreases towards the mass of an “Earth.”
- Stars that contain higher abundances of metals are more likely to have planets on short-period orbits.
- Multiple planets are common, often in resonant orbits.
- The number of planets increases with distance from the star.
- Eccentric orbits are common, with only 10% of planets being on nearly circular orbits.

About 85% of these planets are more massive than Saturn (95 Earth-masses). However, of the 15% that are less massive, some are very much less massive. Microlensing has found evidence for a planet as low in mass as 5.5 Earth-masses, less than the 7.5 Earth-mass record found by radial-velocity techniques to date. These objects suggest that a second and perhaps third class of extrasolar planet has been found, beyond the gas giants: Super-Earths (large rocky planets, suggested from the evidence of radial velocity detections of short-period planets with gas giant siblings on longer-period orbits) and ice giants (suggested from microlensing detections of 5.5 Earth-masses and above on ~ 2.5 AU orbits). The increasing number of planets with smaller mass implies that planets with masses below 5.5 Earth masses, currently undetectable, are even more numerous. Moreover, the correlation with heavy elements supports current planet-formation theory that suggests rocky planets would be more numerous than the gas giants. The observations suggest that many nearby stars harbor rocky planets.

Although it is possible that the radial-velocity technique could reduce its noise level to about 0.1 m/s, low enough to detect Earth-mass planets, at present this has not been demonstrated, and if it is, it may only be applicable to stars that are intrinsically low in radial velocity noise. To move to lower-mass planets, we will employ two space telescopes: Kepler and SIM PlanetQuest.

Kepler will monitor over one hundred thousand distant stars looking for rare transits of planets as small as Mars as they pass in front of their parent stars. It will photometrically monitor 100,000 stars up to 600 pc away, and it should discover tens of terrestrial planets and hundreds of gas-giant planets. From Kepler we will derive a statistical knowledge of how rare or common planets like Earth are.

SIM PlanetQuest will perform the first census of terrestrial planets around the nearest stars — planets that we will be able to observe through direct detection of light to learn more about their physical properties, accurately measuring their masses and orbits. SIM PlanetQuest will have the ability to determine the complete catalog of planetary and orbital parameters needed to understand planetary systems down to several Earth masses and a few astronomical units from their stars. SIM PlanetQuest will detect the “wobble” in the parent star’s apparent motion as the planet orbits, to an accuracy of one millionth of an arcsecond — the thickness of a nickel, viewed at the distance of the Moon. SIM PlanetQuest’s census of nearby stars will optimize target selection for TPF-C, and will improve the latter’s observing efficiency and sensitivity, speed the rate of discovery, and ultimately enhance our ability to characterize the planets we find.

In their respective roles, Kepler and SIM PlanetQuest are highly complementary: Kepler provides statistics on the frequency of Earth-size planets using distant stars, and SIM PlanetQuest surveys the nearest stars to find targets suitable for subsequent observation by the Terrestrial Planet Finder missions.

2.4 Search for Habitable Planets and Life

To determine whether a planet is habitable, we must build observatories capable of directly detecting the light from the planet, with the planet illuminated by the light of its parent star or glowing at infrared wavelengths by the warmth of the planet itself. The direct detection of Earth-like planets is an enormous technical challenge; telescopes are required that can suppress the overwhelming glare from a star so that its faint orbiting planets can be seen. At mid-infrared wavelengths, a typical star would be a million times brighter than an Earth-like planet in its orbit, and at optical wavelengths the star may appear a billion times brighter than the planet. The detection of other Earths has been compared to detecting a firefly in the glare of a searchlight — on a foggy night — where the observer is above the Pacific coast and the searchlight and firefly are above New York.

The search for habitable planets and life is founded upon the premise that the effects of even the most basic forms of life on a planet are global, and that evidence for life, or biosignatures, from the planet's atmosphere or surface will be recognizable in the spectrum of the planet's light. Observations across as broad a wavelength range as possible are needed to fully characterize a planet's ability to support carbon-based life and to search for signs of life.

Direct imaging detection and spectroscopic characterization of nearby Earth-like planets will be undertaken by the Terrestrial Planet Finder missions. The TPF Coronagraph (TPF-C) will operate at visible wavelengths. It will suppress the light of the central star to unprecedented levels, allowing it to search for terrestrial planets in ~ 150 nearby planetary systems. The TPF Interferometer (TPF-I) will operate in the mid-infrared and will survey a larger volume of our solar neighborhood, searching for terrestrial planets around up to 500 nearby stars.

Characterize Extrasolar Giant Planets

The characterization of extrasolar gas-giant planets is the logical first step along the path to the discovery of other Earths. The first successes will doubtless be with young Jupiters, orbiting at tens of astronomical units from their young parent stars; during their (short) accretion phase these newly formed planets are thousands of times brighter in the infrared than planets that have cooled off with age. For gas giants, near- or mid-infrared spectra, even at low spectral resolution would yield temperatures and the abundances of key chemical species such as water, methane, and ammonia. Direct detection will also enable time- and phase-resolved observations of planetary brightnesses, orbital motions, and planetary rotation; and it will allow detailed studies of the time-dependent composition of their atmospheres.

Ground- and space-based transit observations have already been used to characterize 16 of the transiting giant planets that are presently known. HST observations of the giant planet HD 209458b have shown sodium in its atmosphere, yielding the first-ever composition measurement of a planet outside the Solar System. Spitzer has observed the passage of this same planet (as well as TrES-1) behind its star, thus measuring the drop in total light and allowing the temperature of the planet to be determined. In cases where transits have been measured and radial velocity data are available, the planet mass can be accurately measured.

Table 2. Synergy of Missions in the Navigator Program

PARAMETERS	SIM	TPF-C	TPF-I
Orbital Parameters			
Stable orbit in habitable zone	✓	✓	✓
Characteristics of Habitability			
Temperature			✓
Temperature variability due to distance changes	✓	✓	✓
Radius		◆	◆
Albedo		◆	◆
Mass	✓		
Surface gravity	◆	◆	◆
Atmospheric and surface composition		✓	✓
Atmospheric conditions		✓	✓
Presence of water		✓	✓
Temporal variability of composition		✓	✓
Solar System Characteristics			
Influence of other planets	✓		
Presence of comets or asteroids		✓	
Indicators of Life			
Atmospheric biosignatures (e.g., O ₂ , O ₃ , CH ₄)		◆	◆
Surface biosignatures (e.g., vegetation red edge)		✓	

- ◆ = all the missions are required to determine the parameter
- ✓ = parameter can, in principle, be obtained by one mission alone

Follow-up studies of known transits using ground-based 30-m class telescopes, SOFIA, and space telescopes (e.g., Spitzer, JWST, Herschel, and SIM PlanetQuest) will provide more detailed information. The Kepler mission can measure the tiny change of the system’s total brightness of planet and star as the planet orbits from “new” to “full moon” phase, for close-in Jovian planets.

Ground-based interferometry with the Keck Interferometer and the Large Binocular Telescope Interferometer also provides a path to the detection and characterization of extrasolar giant planets. A next-generation infrared interferometer in Antarctica could detect many young Jupiters and perhaps a few mature gas giants in reflected light around the nearest stars.

In the coming decade, a space-based Discovery-class mission would enable the detection and characterization of giant planets using high-contrast imaging and low-resolution spectroscopy. This would lead to a major near-term advance in understanding of the nature of gas giants, their formation and evolution, and the planetary systems in which they occur.

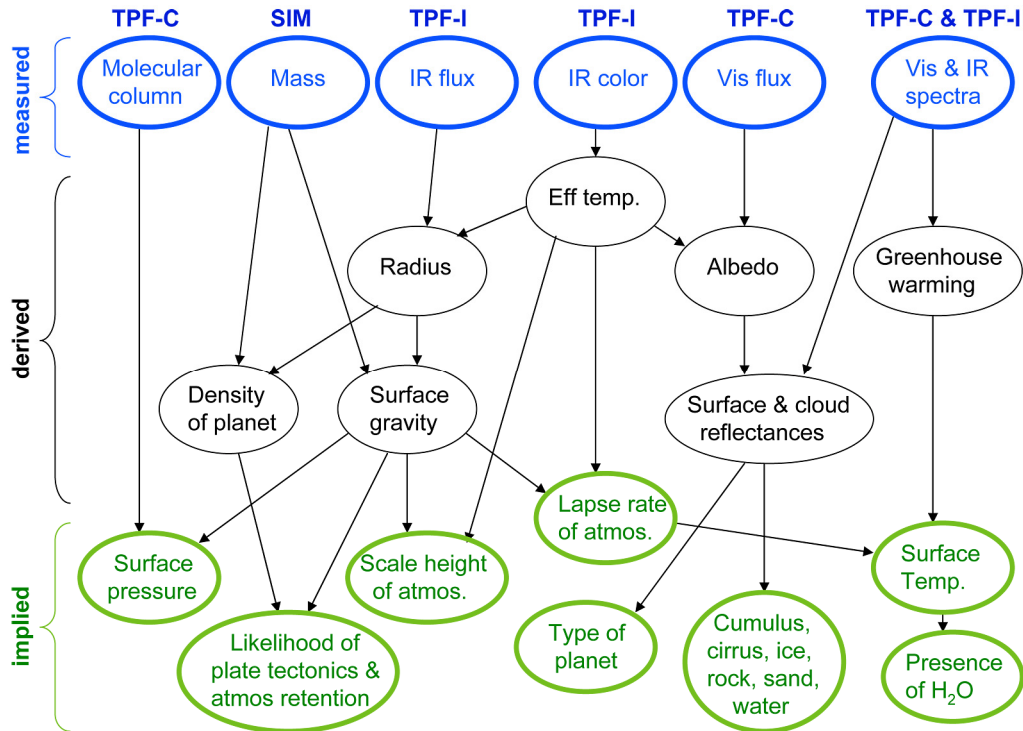


Figure 1. Mission synergy leads to exoplanet properties. The flow-down from mission data to derived properties and finally to implied physical properties of an exoplanet is shown schematically in this diagram. For example, TPF-I will measure a planet's infrared flux and color, from which the effective temperature and radius can be derived. Then using SIM's measurement of mass we can derive the mean density and surface gravity of the planet. Finally, these derived quantities can be used to imply whether a planet has plate tectonics, and also whether it can retain its atmosphere. (W. A. Traub, JPL)

For nearby stars, and as a precursor to the TPF missions, SIM PlanetQuest will provide the most accurate and most comprehensive statistics on Jovian planet masses; SIM PlanetQuest is particularly sensitive to planets in the outer region of planetary systems (2 to 5 AU) where gas giants are likely to be more populous. Indirect information from astrometry and transits, together with theoretical analysis, will expand our knowledge of giant planets beyond the few examples in our own Solar System, and will tell us a great deal about their atmospheres and interiors, including the likely composition of their mysterious central cores.

Characterize Terrestrial Planets

Thorough characterization of a planet is a fundamental part of the search for life. The exploration of our own Solar System and ongoing astrobiology research have taught us that signs of life can only be conclusively recognized in the context of the overall planetary environment. The diversity of rocky worlds is likely much greater than that represented by Mercury, Venus, Earth, and Mars. SIM PlanetQuest, TPF-C, and TPF-I will begin the process of exploring these new planets by measuring their fundamental properties, many of which have strong interdependencies. Table 2 summarizes the scientific synergies between these missions. The derived and implied parameters that can be obtained are further illustrated in Figs. 1 and 2.

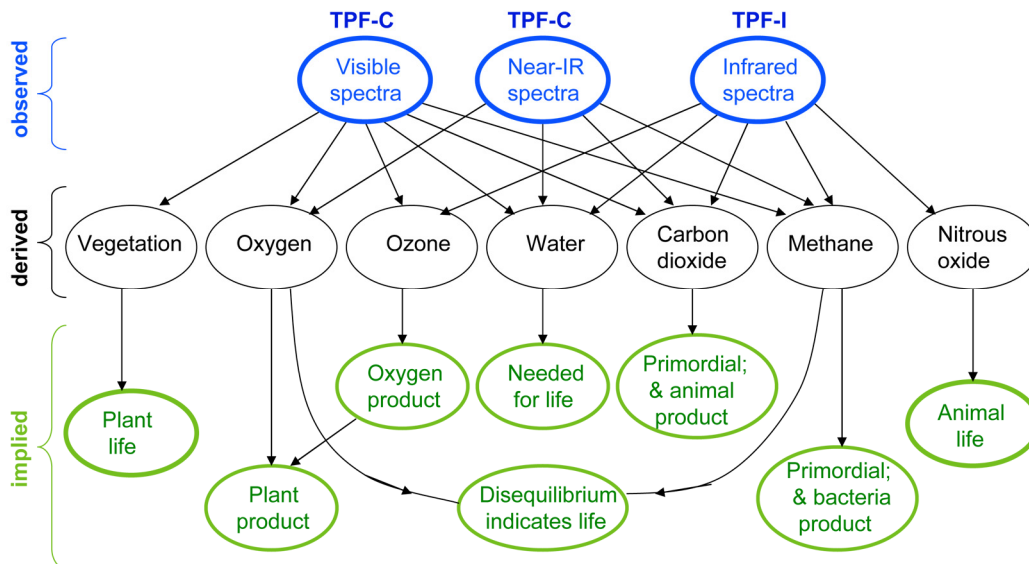


Figure 2. Mission synergy leads to signs of life. For example, TPF-C will measure visible spectra from which the oxygen abundance can be estimated, and TPF-I will measure mid-infrared spectra from which the methane abundance can be estimated. If these species have Earth-like abundances, then we can infer that the atmosphere is in chemical disequilibrium, which is a strong indicator of life on the planet. (W. A. Traub, JPL)

Mass. The SIM PlanetQuest mission will directly measure the masses of the larger rocky planets, providing a fundamental planetary property, and discriminating ice-giants from rocky planets that might otherwise have similar brightnesses. The geochemical and thermal structure of the interior of a planet depends on the planet’s mass. A more massive rocky planet, with a liquid metallic core, is also more likely to have plate tectonics that can recycle surface material (to maintain habitability over long periods) or generate a planet-wide magnetic field that can protect the surface from cosmic rays. A planet’s ability to retain an atmosphere also depends on its mass. A substantial atmosphere (~1 bar) contributes to habitability by reducing large surface-temperature variations, and by producing greenhouse effects, which can raise the surface temperature to support liquid water.

Temperature and Radius. The effective temperature of rocky planets (the temperature of the observed or “emitting” surface (which may be the actual surface, or a cloud deck or other atmospheric level) will be best measured by combining TPF-C and TPF-I data with SIM PlanetQuest orbital measurements. By combining TPF-C measurements of the reflected visible fluxes with the mid-infrared fluxes made by TPF-I, we can constrain the radius, surface reflectance (albedo), and effective temperature of the emitting surface. For planets with atmospheres, spectroscopic observations of greenhouse gases and other atmospheric properties by both TPF-C and TPF-I can be combined with atmospheric models to infer the surface temperature and pressure, which are our best indicators of habitability.

Atmospheric Composition. TPF-C and TPF-I will acquire low-resolution spectra of planets to measure the chemical composition and physical properties of their atmospheres. The spectroscopic observations will be designed to detect oxygen, ozone, carbon dioxide, methane, other absorbing gases, and clouds (if present) in the planet’s atmosphere. These spectroscopic observations will be essential to our search for signs of habitability and life.

Surface Properties. TPF-C and TPF-I will search for temporal variability in the brightness of the planets caused by the rotation of surface features and clouds. For planets that are not entirely covered by clouds, TPF-C can get direct spectral measurements of planetary surface composition (rock, ocean, ice, vegetation). TPF-I may also be able to constrain the surface composition on these planets. These observations will be used to determine whether the planet has clouds, oceans, and continents. Spectral observations at different points in the planet's orbit will be used to search for seasonal global variations in planetary properties. Because of the relatively slow rate of change of the planet-wide physical properties being considered here, it will be possible to combine the TPF-C and TPF-I data sets in a meaningful manner after taking into account orbital location, phase-function effects, etc.

SIM PlanetQuest and the TPF missions will thus not only determine if there are terrestrial planets around nearby stars, but will also explore their suitability for hosting life. This work will phase directly into the next and most exciting step in the science program — the search for actual signs of present or past life on the most promising candidates.

Search for Life beyond our Solar System

The search for life elsewhere in the Universe begins with an understanding of the biosignatures of our own world. Earth has surface biosignatures due to vegetation, and several atmospheric biosignatures, including the characteristic spectra of life-related compounds like oxygen — produced by photosynthetic bacteria and plants — and its photochemical product, ozone. The most convincing spectroscopic evidence for life as we know it is the simultaneous detection of large amounts of oxygen and a reduced gas, such as methane. Nitrous oxide is produced by living organisms, and its detection would also be a very convincing sign of life. Oxygen, methane, and nitrous oxide are produced in large amounts by plants, animals, and bacteria on Earth today, and they are orders of magnitude out of thermodynamic equilibrium with each other.

However, we should not expect other habitable worlds to be exactly like our own. We must furthermore be able to identify potential “false-positives,” the non-biological generation of planetary characteristics that mimic biosignatures. For example, while atmospheric methane may be a possible biomarker on a planet like Earth, especially when seen in the presence of oxygen, on a body like Titan it is simply a component of the atmosphere that is non-biologically generated. Theoretical and experimental research and analysis is a crucial part of our quest for life. We must have a detailed understanding of the biosignatures that might be found. This is especially true for habitable planets that differ from modern Earth in age or composition. The results of this research will help set the requirements for the Terrestrial Planet Finder missions and aid in the design of even more advanced future telescopes. These ongoing studies are supported by the NASA Astrobiology Institute and the TPF-Foundation Science program.

By characterizing the basic properties of planets, the planned suite of missions will determine whether any of the nearby planets have suitable environments for detectable life. The TPF-C and TPF-I missions will make intensive observations of the systems that contain a terrestrial planet in the habitable zone and explore the planet's brightness and spectrum in detail. TPF-C and TPF-I will have sufficient spectroscopic capability to detect evidence for gases such as carbon dioxide or water vapor. The visible and infrared spectrum, in conjunction with theoretical and empirical models, can tell us about the amount of atmosphere, the gases present in the atmosphere, the presence of clouds, the degree and variability of cloud cover or airborne dust, and the presence of a greenhouse effect. The concentration of greenhouse gases can

determine whether the surface is warm enough to maintain liquid water, even if (as for Earth) the equilibrium temperature without such gases would result in a frozen surface. Clouds and dust aerosols can determine the amount of light absorbed and reflected, and, thus, the surface temperature. Spectra can also tell us about the surface, whether it is rock-like with little or no overlying atmosphere, or covered with an ocean.

Beyond the TPF missions, the next-generation Life Finder mission would use a greater collecting area and spectral resolution to provide a more sensitive search for additional biosignatures and extend our search for Earth-like worlds to perhaps thousands of stars. The dual goals of extending our search to more planetary systems and providing greater time-resolved spectral information will challenge our imagination and technical prowess for decades to come. The Decadal Review (*Astronomy and Astrophysics in the New Millennium, 2001*) strongly endorsed the search for life beyond our Solar System, noting that “*This goal is so challenging and of such importance that it could occupy astronomers for the foreseeable future.*”

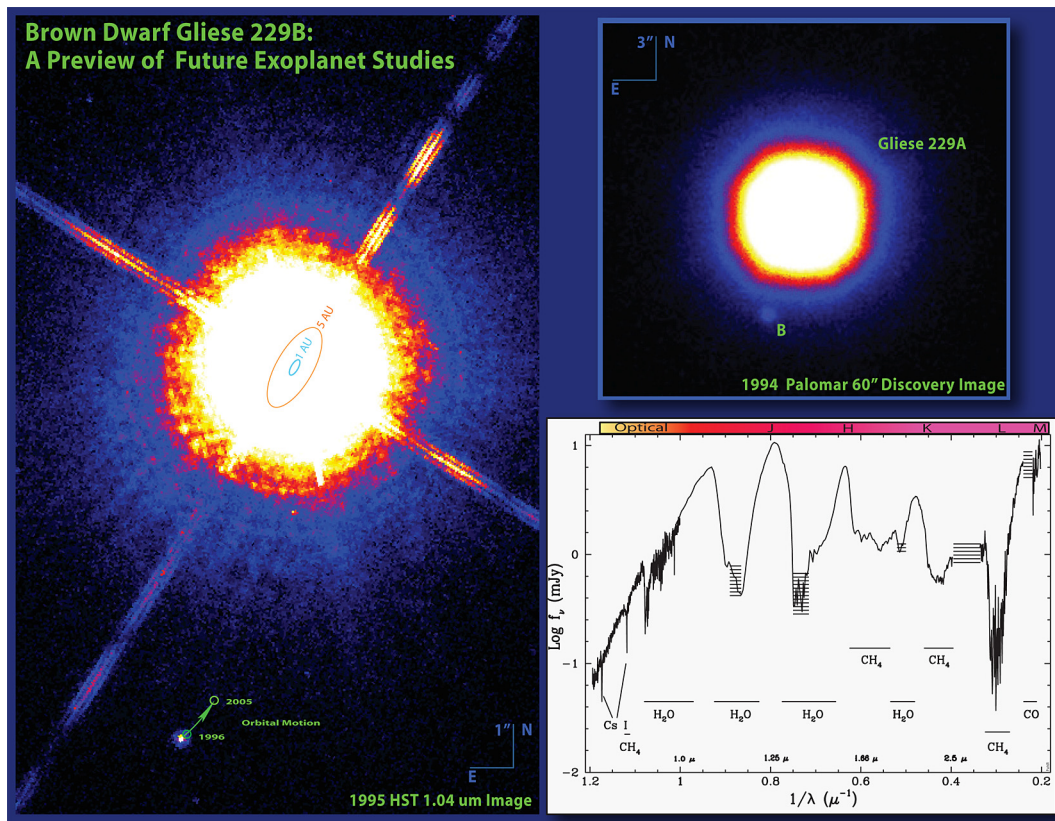


Figure 3. Spectroscopic study of Gliese 229B. The brown dwarf Gliese 229B is shown in the left panel (the faint object towards the bottom of the panel) with its known orbit indicated. The discovery in 1994 (top right) and subsequent spectroscopic study of this object (bottom right) through ground-based coronagraphy, adaptive optics, and spectroscopy provide a direct precursor example of the type of studies of exoplanets that the Navigator Program seeks to conduct. Shown here are details of the atmospheric chemistry, internal physics, and orbital motion of this low-mass companion. (B. Oppenheimer, American Museum of Natural History).

2.5 Navigator Program

In support of NASA's vision to develop advanced telescope searches for Earth-like planets, the Navigator Program was created. The Navigator Program is a suite of inter-related missions to explore and characterize new worlds. The program embodies the presidential directive to enable advanced telescope searches for Earth-like planets and habitable environments around neighboring stars. Each successive mission provides an essential step toward the ultimate goal of revealing signs of life elsewhere in the universe. The Navigator Program is structured in a cohesive effort leading towards the Terrestrial Planet Finder missions, which serve as the focus of the program. The relationship between the different missions is illustrated in Fig. 4. The search will begin in this decade with the Keck Interferometer and the Large Binocular Telescope Interferometer, which will observe nearby stars to probe exozodiacal dust disks, thus revealing gaps and features created by planets that have so far remained unresolved. The stage will then be set for more advanced telescope searches in space that are capable of detecting Earth-like planets.

Navigator Program Objectives

NASA's Navigator Program is a scientific program whose primary goals are to detect and characterize Earth-like exoplanets and to understand the formation, history, and distribution of planetary systems in our Galaxy. A secondary goal is to pursue the understanding of the formation and evolution of stars, planets, and galaxies. The program consists of a series of interrelated space and ground-based missions and science center activities with the long-term goal of finding evidence of life on nearby planets. The missions that are now included in the Navigator Program are the result of approximately two decades of scientific, technological, and engineering planning and development in order to accomplish the measurements necessary to achieve the program goals. There are additional observatories and space missions developed by NASA, ESA, NSF, European Southern Observatory (ESO), etc. that also have contributed and will continue to contribute measurements that support these goals. As our scientific understanding in this emerging field advances, so will our understanding of the best methods to make further measurements; this may in turn lead to changes in the missions the Navigator Program intends to develop.

The volume of space that would be explored would be limited to the closest stars because of the technical difficulty of discriminating the light from a planet from that of its parent star. In this context "nearby" is understood to be stars that lie within approximately 20 pc (60 light years) from our Sun. This is roughly the distance that we can explore using technology available in the next decade.

Key features of the Navigator Program include:

- Integration of space and ground activities into a cohesive effort to find and characterize the planetary systems in our solar neighborhood. Each project will build upon the prior projects' activities, both in terms of science results and technological advancements, in order to enable the discovery and characterization of terrestrial planets in these systems.
- A multi-project approach to managing risk across the Navigator Program, by identifying the scientific and technological dependencies across the program and developing alternatives and scopes to provide program robustness and flexibility.

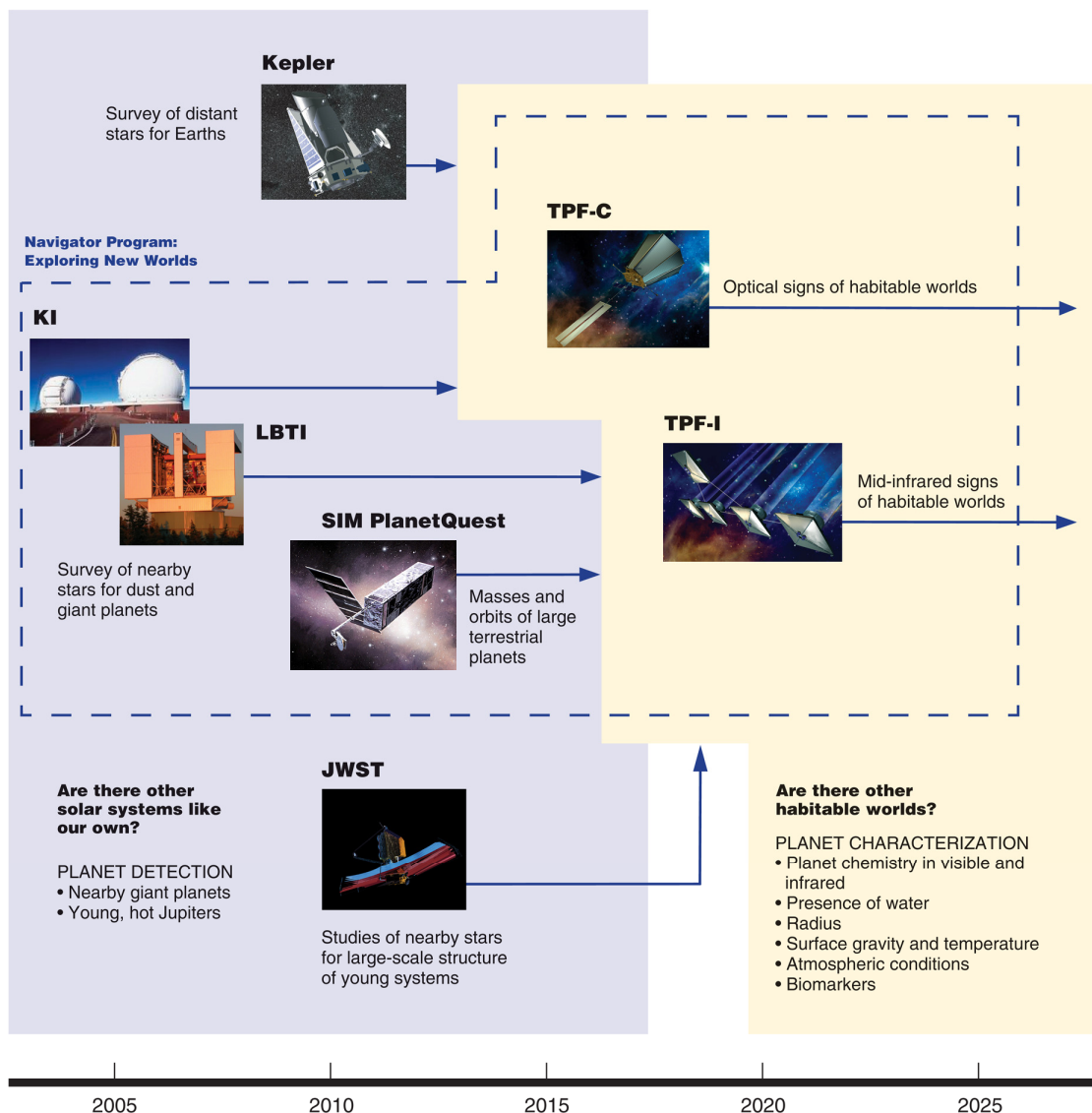


Figure 4. Are there other planetary systems like our own? Are there other habitable worlds? These are two of the fundamental questions being addressed by the Navigator Program. Shown above is a notional timeline indicating the flow of science between missions, including the Kepler Discovery mission and the James Webb Space Telescope.

The Navigator Program includes flight projects as well as ground-based projects, technology development and supporting activities in a cohesive effort directed to the accomplishment of the goals and objectives derived from the NASA’s Strategic Plan and assigned to the Navigator Program.

The Navigator Program is being developed at a time when new planets are being found every month. A thorough understanding of new scientific discoveries is of utmost importance to the optimum design of the missions in the program. For example, although it is estimated that 10-Earth-mass planets exist around roughly 40 percent of stars, the frequency of Earth-like planets is at present unknown — since Earth-mass planets have not yet been detected. Precursor missions and ongoing ground-based science will provide

detailed statistics of other planetary systems that will help mature the technology requirements and mission designs. NASA's fostering of the science of exoplanets, as well as its engagement of scientists and students, through NASA research opportunities and other funding sources provides a solid foundation for the Program.

An Integrated Program

Technology for Planet Finding

The Navigator Program encompasses a cohesive set of flight and ground activities that have a common scientific purpose and share many technological challenges. The common framework for technology and project development benefits all Navigator missions. Each major mission in the Navigator Program builds upon the scientific and technical legacy of past missions and develops new capabilities for those that follow.

The technological challenge is essentially one of high-dynamic range sensing coupled with high angular-resolution imaging. This is true because exoplanets appear in the sky as extremely faint objects located in extremely close proximity to their host stars. The light from the planet must first be resolved separately from the starlight, and the glare of the starlight must be then be suppressed to allow atmospheric spectroscopy of exoplanets. The technology required for finding planets will also allow observations of other extremely faint and previously unresolved targets. The scope of science included in the Navigator Program is therefore broader than the search for planets, including within its theme diverse topics related to the origin and evolution of stars, planets, and galaxies.

Navigator Foundation Science

A broad community of scientific endeavors, spanning all aspects of experimental and theoretical research in planet finding, is supported by the Navigator Program through the NASA-supported TPF Foundation Science. The suite of Navigator science and the excitement of planet finding are conveyed to the public through a unified education and public outreach effort, most visible through Navigator's award-winning PlanetQuest website (<http://planetquest.jpl.nasa.gov/>).

Michelson Science Center and Michelson Fellowship Program

Common resources for mission and community support are coordinated within the Navigator Program. As part of its portfolio of activities for finding exoplanets, the Navigator Program includes the Michelson Science Center (MSC). The MSC is named in honor of Albert Michelson, the first American to receive the Nobel Prize in physics and the pioneer of laboratory and astronomical interferometry. The primary purpose of the MSC is to develop the science and technology of detection and characterization of planets and planetary systems about other stars.

The center provides common resources for data processing, archiving, and support for new observers; the Michelson Fellowship Program, managed through the MSC, provides support to a new generation of young graduate students and scientists engaged in Navigator science and technology. The MSC actively promotes its services in the astronomical community and is host to practitioners of techniques specific to this endeavor, including interferometry, coronagraphy, and astrometry. Projects of this nature that are too large

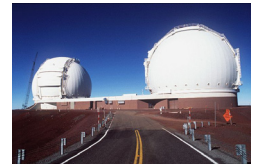
or require specialized expertise beyond that of a typical university department are particularly well served by the MSC, including support of the Keck Interferometer and SIM PlanetQuest missions. Supporting activities, such as proposal administration, long-term archives, community workshops, and fellowship oversight, are also part of the MSC's mandate from NASA to expand our knowledge of planets about other stars.

Navigator Program Missions

Keck Interferometer (KI)

NASA supports a broad science program in conjunction with the W.M. Keck Observatory in Hawaii. This program has two main thrust areas: first the sponsorship of community-accessible time on single Keck telescopes to pursue strategic science goals; and second, the development and operations of the Keck Interferometer (KI).

The single-Keck program has been in place since 1996, and it has been extremely successful in producing important scientific results such as radial velocity exoplanet detections, spectral characterizations of L and T dwarfs, and mid-infrared imaging of planetary debris disks. KI has combined the infrared light collected by the two 10-m Keck telescopes to undertake a variety of astrophysical investigations. The main issue to be addressed by KI will be the location and amount of zodiacal dust in other planetary systems. This first in-depth census of dust will be an important contribution to our understanding of the architecture and evolution of planetary systems, and will be key in helping to define the requirements and the architecture for TPF.



Large Binocular Telescope Interferometer (LBTI)

The Large Binocular Telescope Interferometer (LBTI) will further a variety of NASA strategic goals in star and planet formation through both nulling and wide-field imaging interferometry. Primary among these goals is a planned systematic survey of nearby stars to understand the prevalence of zodiacal dust and gas-giant planets and to determine a system's suitability for terrestrial planets. The modest baseline and common mount design of the dual 8.4-m LBTI allows uniquely sensitive infrared observations of candidate planetary systems through nulling interferometry. The development of nulling technology and observing techniques will help create a mature technological basis for a TPF mission. The LBTI also allows wide-field, high-resolution imaging of objects down to brightness levels similar to the limitations of filled-aperture telescopes.

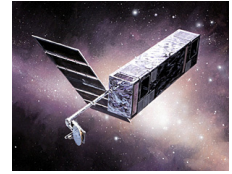


The Keck Interferometer and Large Binocular Telescope Interferometer will:

- Image dust disks around nearby stars to estimate the density of material in the habitable zone.
- Search for gaps and asymmetries in dust disks indicative of perturbations by planets.

Space Interferometry Mission (SIM) PlanetQuest

The **Space Interferometry Mission (SIM) PlanetQuest** will be the first observatory capable of detecting and measuring the mass of planetary bodies with a few times the mass of Earth in orbit around nearby stars. SIM PlanetQuest will take a major step forward in answering these questions for nearby stellar systems: Are we alone? Are there other worlds like our own home planet, existing within planetary systems like our own Solar System?



SIM will extend our exploration of nearby planetary systems into the range of the rocky, terrestrial planets on habitable orbits around Sun-like stars, permitting scientists to refine their theories of the formation and evolution of planets like Earth. This census will form the core of the observing programs for subsequent missions that will investigate in detail the nature of these newly discovered worlds. SIM will aid in defining the early target list for TPF by identifying systems to focus on—those with candidate planets of a few Earth masses in the habitable zone, or those with a dynamical void that would imply the presence of such planets. SIM will also help identify systems to avoid, such as those with giant planets near the habitable zone. Orbital information from SIM could help in detailed planning of TPF observations. SIM will provide for the first time the properties of planetary systems in orbit about young stars where imaging is limited by photospheric activity and rapid rotation, helping to answer questions about the formation of these systems. SIM will provide all-important data on planetary masses, which (when coupled with data from TPF-C/I)

Table 3. Overview of Missions in the Navigator Program

Science Theme & Mission Name	Wavelength Range	Observatory Design	Sensitivity and Resolution
Exozodiacal Dust and Hot Jupiters			
Keck Interferometer	10- μ m nulling waveband	Ground-based interferometer with two 10-m telescopes, 85-m baseline	1–10 zodi at 0.1–1.0 AU
Large Binocular Telescope Interferometer	10- μ m nulling waveband	Ground-based interferometer with two 8.4-m telescopes, 14.4-m center to center	1–10 zodi beyond 1 AU
Astrometric Detection of Terrestrial Planets			
SIM PlanetQuest	400–1000 nm	Space-based interferometer, multiple 30-cm telescopes with 9-m baseline	Planet finding astrometry with 1 μ as; global astrometry with 3.5 μ as
Planetary Atmospheres, Habitability, Signs of Life			
Terrestrial Planet Finder Coronagraph	500–800 nm, R = 70	Space coronagraphic telescope with a 3.5 \times 8-m elliptical primary	35 core stars, plus 130 additional main-sequence stars: O ₂ , O ₃ , H ₂ O
Terrestrial Planet Finder Interferometer	6.5–17 μ m, R = 20	Space-based interferometer, four 4-m formation-flying telescopes	35 core stars, plus 130 additional main-sequence stars: CO ₂ , H ₂ O, and O ₃

will yield densities and surface gravities crucial to complete physical characterization. In addition to its scientific goals, SIM will develop key technologies that will be necessary for future missions, including precision location of optical elements to a fraction of the diameter of a hydrogen atom (picometers) and the precise, active control of optical pathlengths to less than a thousandth the diameter of a human hair.

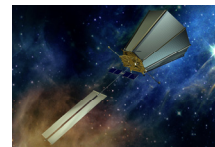
Beyond the detection of planets, SIM's extraordinary astrometric capabilities will permit determination of accurate positions throughout the Milky Way Galaxy (as described in Chapter 7). This will permit studies of the dynamics and evolution of stars and star clusters in our galaxy in order to better understand how our galaxy was formed and how it will evolve. Accurate knowledge of stellar positions within our own galaxy will allow us to calibrate luminosities of important stars and cosmological distance indicators, enabling us to improve our understanding of stellar processes and to measure precise distances throughout the Universe.

SIM PlanetQuest will:

- Search for terrestrial planets around nearby stars and measure planetary masses.
- Characterize the orbital ellipticity and inclination of multiple-planet systems to determine the stability and the evolution of planetary systems.
- Search for Solar System analog systems with giant planets at 2–5 AU.
- Perform the only census for gas giants near the habitable zones around young stars (1–100 Myr).
- Investigate formation and migration scenarios that might explain the puzzling presence of hot Jupiters in very short-period orbits.
- Optimize target selection for TPF-C.

Terrestrial Planet Finder Coronagraph (TPF-C)

The Terrestrial Planet Finder Coronagraph (TPF-C) will directly detect and study planets outside our Solar System from their formation and development in disks of dust and gas around newly forming stars to their evolution and even potential suitability as an abode for life. By combining the high sensitivity of space telescopes with revolutionary imaging technologies, TPF will measure the size, temperature, and placement of terrestrial planets as small as Earth in the habitable zones of distant planetary systems as well as their gas giant companions. In addition, TPF spectroscopic capability will allow atmospheric chemists and biologists to use the relative amounts of gases like oxygen, carbon dioxide, water vapor, ozone and methane to find whether a planet someday could or even now does support life. Our understanding of the properties of terrestrial planets will be scientifically most valuable within a broader framework that includes the properties of all planetary system constituents, including gas giants, terrestrial planets, and debris disks. TPF's ability to carry out a program of comparative planet studies across a range of planetary masses and orbital locations in a large number of new planetary systems is an important scientific motivation for the mission. However, TPF's mission will not be limited to the detection and study of distant planets. An observatory with the power to detect an Earth orbiting a nearby star will also be able to collect important new data on many targets of general astrophysical interest.



As currently planned, the visible-light coronagraph will use a single telescope with an 8×3.5 -m mirror operating at room temperature and required to achieve a ten-billion-to-one image contrast in order to isolate the signal of a planet from that of its parent star. Very precise, stable control of the telescope optical quality

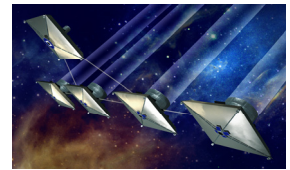
will be required. TPF-C has carried out an extensive program of technology development along multiple paths to enable this unprecedented capability, and has now demonstrated in laboratory conditions the ability to produce contrasts of 10^9 in narrow bands.

TPF-C will:

- Characterize environments of terrestrial planets using visible-light spectroscopy.
- Combine spectra with SIM PlanetQuest masses to robustly characterize the planet and its atmosphere.
- Image dust disks around nearby stars to help build a complete picture of the formation of planetary systems.
- Combine detections with SIM PlanetQuest detections to derive masses down to one Earth mass.
- Determine which planets have conditions suitable for life.
- Search for signs of life.

Terrestrial Planet Finder Interferometer (TPF-I)

The TPF-Interferometer (TPF-I) will be a long-baseline interferometer operating in the infrared. TPF-I will use multiple, 3–4-m-diameter telescopes configured as an array operated on separated spacecraft over distances of a few hundred meters. The telescopes will operate at extremely low temperatures of ~40 kelvin, and the observatory will necessarily be large. However, the image contrast requirement is “only” a million to one, and thus, the required system optical quality will be less challenging at infrared wavelengths than the TPF-C challenge of ten-billion-to-one at visible wavelengths.



The European Space Agency (ESA) has been actively studying an infrared interferometer, referred to as Darwin, with essentially the same science goals as TPF-I. Under a NASA/ESA Letter of Agreement, scientists and technologists in both agencies are discussing ways in which the preliminary architecture studies can lead to effective collaboration on a joint mission.

TPF-I will:

- Characterize terrestrial planet environments using mid-infrared spectroscopy
- Combine detections with those of SIM PlanetQuest and TPF-C to derive a full set of physical parameters describing a planet and its atmosphere — including temperature, surface gravity, etc.
- Image dust-enshrouded protoplanetary disks with milliarcsecond resolution to cleanly separate protoplanets or planets from the disk and star.
- Combine detections with SIM PlanetQuest detections to derive masses down to one Earth mass.
- Determine which planets have conditions suitable for life.
- Search for signs of life.

2.6 Summary of Contributing NASA Missions

Stratospheric Observatory for Infrared Astronomy (SOFIA)

The Stratospheric Observatory for Infrared Astronomy (SOFIA) will study sites of star formation, study formation of new planetary systems, survey the debris disks (which are planet-forming regions), and study Neptune-sized and larger exoplanets through the transit technique. In addition, SOFIA will conduct a number of other astrophysics investigations (such as observations of the cold interstellar medium and of the center of our galaxy) at high spatial resolution at far-infrared wavelengths. SOFIA is a joint U.S. (80%) and German (20%) observatory that consists of a Boeing 747 aircraft with a telescope as large as HST (2.5 m). SOFIA will also function as a unique platform for developing, testing, and reducing risk of new IR instrument technologies, particularly detectors for future missions such as SAFIR. It will have a prominent education and public outreach program, involving high school teachers and students in its flights and observations.

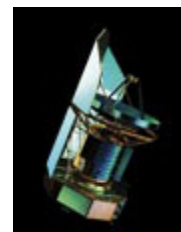


SOFIA will:

- Provide high-resolution images of planetary debris disks around nearby stars.
- Search for the spectral signatures of planet formation in the habitable zones of young stars.
- Observe transits of large exoplanets.

Herschel Space Observatory

The Herschel Space Observatory is ESA's fourth Cornerstone Mission and deploys a passively cooled 3.5-m telescope to observe the far-infrared and submillimeter universe. Herschel is planned as a three-year observatory mission, with a launch date scheduled for early 2007. It will be launched on the same vehicle as the Planck Surveyor mission. Both missions will orbit independently around the second Earth–Sun Lagrange point. Herschel has three instruments, which cover the wavelength range from 57 to 670 μm . Herschel will investigate the birth of stars and their influence on the interstellar medium, and it will be able to identify specific molecules in the inter-stellar medium (ISM). Herschel is a precursor to SAFIR.



Herschel will:

- Find cold material in the outer debris disks around nearby stars corresponding to our own outer Solar System regions.
- Inventory water and other gaseous molecules in the disks and clouds around young stars that may be forming planets.

Kepler

Kepler is a Discovery Program mission scheduled for launch in 2008. It is an excellent example of the kind of moderate-scale missions that can contribute to exoplanet science in important ways. The Kepler mission is specifically designed to photometrically survey the extended solar neighborhood to detect and characterize hundreds and perhaps thousands of terrestrial and larger planets in or near the habitable zone and provide fundamental progress in our understanding of planetary



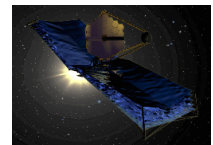
systems. The results will yield a broad understanding of planetary formation, the frequency of formation, the structure of individual planetary systems, and the generic characteristics of stars with terrestrial planets. These results will be instrumental in determining how deep TPF will have to look to find an adequate sample of planetary systems to find and characterize habitable planets. Kepler is a simple 0.95-m Schmidt telescope, with a very challenging detector array consisting of 42 charge-coupled devices (CCDs), each with 2200×1024 pixels.

Kepler will:

- Monitor over one hundred thousand distant stars for transits of planets as small as Earth.
- Derive a statistical knowledge of whether Earth-like planets are rare or commonplace.
- Determine the frequency of planets as a function of planetary radius, orbital period, and stellar type.

James Webb Space Telescope (JWST)

James Webb Space Telescope (JWST) will have an aperture 2.7 times that of HST and about an order of magnitude more light-gathering capability. Because the prime science goals for JWST are to observe the formation and early evolution of galaxies, JWST's greatest sensitivity will be at mid- and near-infrared wavelengths, where the expansion of the Universe causes the light from very young galaxies to appear most prominently.



JWST will be a powerful general-purpose observatory capable of undertaking important scientific investigations into a very wide range of astronomical questions, including those that are central to exoplanet science. JWST will be a powerful tool in the exploration of extrasolar planetary systems by studying planet-forming regions, dust disks and their dynamics, the birth of stars and formation of early systems, and how the chemistry that can lead to life is delivered to planetary systems.

The telescope diameter of JWST will be 6.5 m, and JWST will be celestial background-limited between 0.6 and 10 μm , with imaging and spectroscopic instruments that will cover this entire wavelength regime. JWST has a requirement to be diffraction-limited at 2 μm . With these capabilities, JWST will be a particularly powerful tool for investigating fundamental processes of stellar formation and early evolution, as well as the later stages of evolution. In both cases, dust almost completely blocks our ability to observe the visible light from rapidly evolving stars, so that detailed observations have to be carried out at longer wavelengths.

ESA and the Canadian Space Agency have agreed to contribute significantly to the JWST project. These contributions will be important in significantly enhancing the overall capabilities of the observatory.

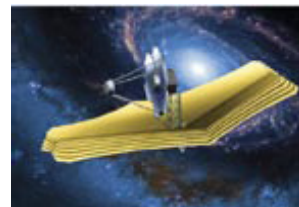
JWST will:

- Probe the epoch of star and planet formation.
- Study the distribution and composition of dust in planetary debris disks.
- Search for young Jupiters around nearby young stars.
- Provide spectroscopic follow-up of gas-giant planets detected by Kepler.

NASA Vision Missions

Single Aperture Far-InfraRed (SAFIR)

The Single Aperture Far-InfraRed mission, consisting of a single 8–10-m telescope and operating in the far infrared, will serve as a building block for the Life Finder (see below) while carrying out a broad range of scientific programs beyond those of JWST and Spitzer. SAFIR will be able to probe the epoch of energetic star formation in the redshift range $1 < z < 10$ at a wavelength regime that can easily detect continuum and cooling-line emission from dust-enshrouded primeval galaxies — with an angular resolution capable of isolating individual objects at or below the limits of the Hubble Deep Field. It will be able to investigate the physical processes that control the collapse and fragmentation of molecular clouds to produce stars of various masses by mapping of cold, dense cores at <100 AU resolution at the peak of their dust emission and using gas phase tracers, such as H_2 , H_2O , CO, [OI], [NII]. By making high spatial resolution maps of the distribution of ices and minerals in the Kuiper Belts surrounding nearby stars, SAFIR will also allow us to investigate the era of cometary bombardment that may have determined the early habitability of Earth. It will also permit studies of the nature of recently discovered objects in the Kuiper Belt of our own Solar System — remnants of our own planet formation process.



SAFIR will:

- Extend Spitzer studies of the temperature structure in circumstellar disks, including characterizing gaps due to planets.
- Provide high-resolution images of planetary debris disks around many stars.
- Search for water and other molecules in the disks and envelopes of young stars that may be forming planets.

Life Finder

Two missions still far in the future because of their demanding technologies have strong relevance to NASA strategic goals. The first is the Life Finder, which would provide high-resolution spectroscopy on habitable planets identified by TPF. This information would extend the reach of biologists, geophysicists, and atmospheric chemists to ecosystems far beyond Earth. Achieving that goal will require observations beyond those possible with TPF. For example, searching the atmospheres of distant planets for unambiguous tracers of life such as methane (in terrestrial concentrations) and nitrous oxide would require a spectral resolution of $\sim 1,000$, using a version of TPF with multiple 25-m telescopes.



Life Finder will:

- Provide additional spectroscopic resolution to detect signs of life beyond those biosignatures available to TPF-C and TPF-I and for planets around many thousands of stars.
- Provide higher time-resolved observations to monitor diurnal and seasonal cycles.

Planet Imager

Finally, in the search for exoplanets capable of harboring life, a mission for the far future that will serve to challenge our imaginations and our technological inventiveness, is Planet Imager. Perhaps using a formation of a dozen 10-m telescopes, this mission may some day return images our children or theirs could use to study the geography of a pale blue planet orbiting a star similar to ours across the gulf of space, time, and imagination. While no clear path to accomplishing this mission currently exists, its appeal is so great that it will remain a distant vision until future generations make the dream a reality.



3 Frequency of Terrestrial Planets

3.1 Objectives of Precursor Science

Relevance to the Navigator Program

The fraction of the number of stars that has at least one potentially habitable planet can be denoted as η_{\oplus} .^{††} The National Research Council decadal-survey report, *Astronomy and Astrophysics in the New Millennium* (2001), highlighted the importance of η_{\oplus} when it noted

The committee's recommendation of this mission is predicated on the assumptions that TPF will revolutionize major areas of both planetary and nonplanetary science, and that, prior to the start of TPF, ground- and space-based searches will confirm the expectation that terrestrial planets are common around solar-type stars. NASA should pursue a vigorous program of technology to enable the construction of TPF to begin in this decade.

The TPF science advisory groups (the TPF-I Science Working Group, and the TPF-C Science and Technology Definition Team) and the Navigator Program recognize the importance of this recommendation both for giving NASA and the public the confidence to proceed with the development of TPF and to define key parameters of the missions. The Navigator Program believes that the best way forward is for TPF-C and TPF-I to be designed as capability-driven missions. The observatories must have an angular resolution and sensitivity capable of detecting and characterizing planets around a sufficient number of stars, such that we can expect to detect and characterize a statistically significant number of terrestrial planets. For example, this may mean having the ability to search all G-type stars out to a distance of 15 pc. How many stars TPF-C and TPF-I will be capable of searching for planets, and how large a volume of space they will search, will ultimately depend on the size of each observatory. The capability of the missions will therefore involve a trade between the expected science return and the technological challenges of building larger observatories. This chapter highlights the techniques that will in this decade advance our understanding of extrasolar planetary systems, build confidence in the mission design, and assist in defining the scope of TPF.

^{††} η_{\oplus} , is described further in Appendix B, listed along with other definitions adopted by the Navigator Program to describe the properties of exosolar planets and their host stars.

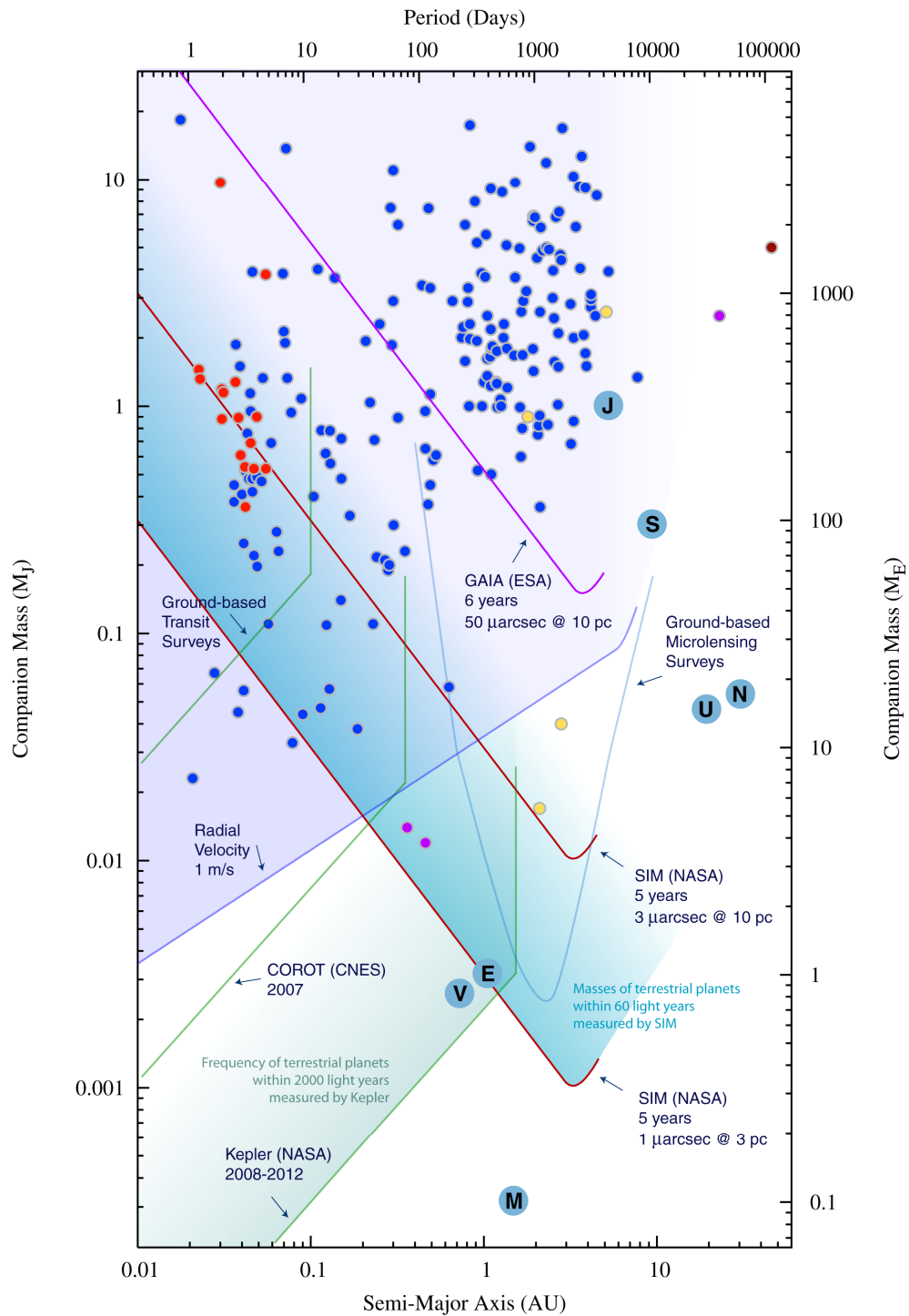


Figure 5. Limiting sensitivity of techniques of planet finding. Shown in the above figure are the sensitivity limits of radial velocity surveys, astrometric surveys, microlensing surveys, and both ground-based and space-based transit techniques. Planets in our Solar System are also indicated. The filled circles indicate the planets found by radial velocity surveys (blue), transit surveys (red), and microlensing surveys (yellow). Also indicated by the filled circles are pulsar planets (violet) and the companion to a young brown dwarf (dark red). The astrometric and radial velocity limits are from equations given by Perryman (2000); the microlensing limit is from Bennett (2006); the transit survey limits are the editors' approximations from available data. The discovered exoplanets shown in this plot represent the planets recorded at *The Extrasolar Planets Encyclopaedia*, <http://exoplanet.eu>, through October 12, 2006. (P. R. Lawson, JPL)

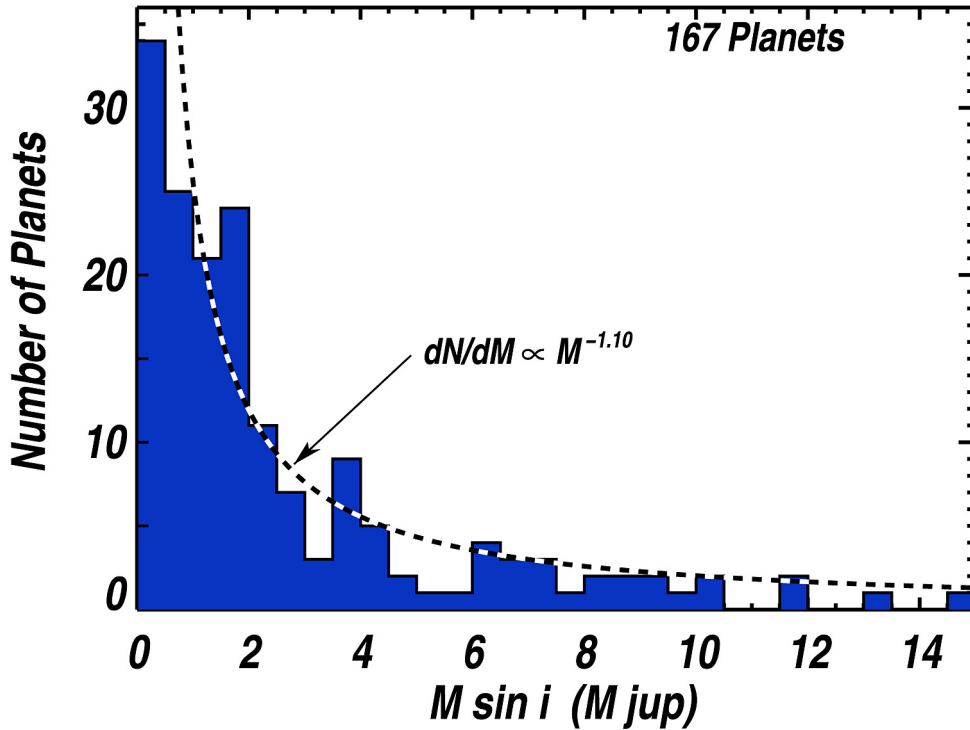


Figure 6. Mass histogram of exoplanets detected by radial velocity surveys. The rising mass-distribution of planets of less than 5 Jupiter masses shows that lower-mass planets are more common than more massive ones. The data represent the 167 nearby planets reported by Butler et al. in July 2006. (Butler *et al.* 2006)

Metrics for Decision Making

Prior to the launch of TPF-C, advances in our knowledge of extrasolar planetary systems are most likely to come from radial-velocity measurements, microlensing, the results of the COROT (CNES) and Kepler (NASA) transit-survey missions, and from planet searches with SIM PlanetQuest (NASA). As shown in Fig. 5, by 2012 our understanding of exoplanets should have advanced sufficiently to allow us to interpolate the distribution of planets across TPF’s region of interest, and in so doing provide an improved estimate of the frequency of Earths.

More certain knowledge of the characteristics of extrasolar planetary systems will allow the TPF Project to determine the scope and science return of the mission prior to entering Phase B. In the latter phases of the project life-cycle, improvements in the statistics of exoplanets will allow a further refinement of the target list and improved scheduling of the mission timeline.

Schedule and Deliverables

Figure 5 shows the wide variety of ongoing or planned observational efforts relevant to studies of exoplanets, in particular the highly successful radial velocity surveys and planned experiments using astrometry, transits, and microlensing. These observational programs progress with time from 2006 up to around 2012, when Kepler will have obtained the first direct results on the incidence of Earth-sized planets

in 1-AU orbits. SIM results will come late enough that they will be primarily of interest in characterizing and prioritizing potential TPF target stars rather than in setting the scope of the mission in advance of Phase B/C/D.

3.2 Observational Programs

Radial Velocity Surveys

Current State of the Art

The spectroscopic measurements used in radial velocity surveys detect the reflex motion of the star in response to the orbiting planet, but because the inclination, i , of the planet's orbit is usually unknown, only a lower limit to the mass is derived: $M \sin i$. Radial velocity precisions of 1–10 m/s have resulted in 93% of the reported gas-giant planets orbiting nearby stars. Values of $M \sin i$ and the semi-major axes of the orbits of these planets were shown previously in Fig. 5. Figure 6 shows a mass histogram of planets detected to date. Radial velocity detections require the observation of at least one full orbital period to detect a planet. As a consequence, this technique first detects planets with short orbital periods. Indeed, most exoplanets with $M \sin i > 0.5 M_J$ and orbital periods less than 1 year have already been culled from the collective planet surveys of the brightest and closest 2500 roughly Sun-like stars. Reflecting the growing time baseline of radial velocity surveys, exoplanet detections since 2002 typically have orbital periods longer than two years. The statistics for stars that have been included in radial velocity surveys for at least 8 years show that:

- 1% of stars have gas-giant planets with orbital periods less than 10 days (hot Jupiters).
- 7% of stars have detectable gas-giant planets in orbits less than 8 years.
- More than half of stars with one detected planet show radial velocity variations indicating the presence of one or more additional gas-giant planets.
- The mass distribution increases toward the low $M \sin i$ detection threshold.
- A wide range of eccentricities is observed: hot Jupiters reside in nearly circular orbits because of tidal interactions; planets with orbital periods between 10 days and several years have $0 < e < 0.7$; and although the statistics are currently poor, the data suggests that gas-giant planets with orbital periods of several years exhibit a lower range of eccentricities (between circular and $e \sim 0.1$ – 0.3).

There have been significant improvements in the past few years in both hardware and software development for échelle spectrometers that have led to radial velocity precisions of 1–3 m/s. With this precision, several Neptune-mass planets have now been detected in short-period orbits.

Expected Near-Term Progress

In order to detect lower-mass or longer-period planets and the intricate details of multiple-planet orbits, the precision and duration of radial velocity surveys must improve. As radial velocity precision improves, astrophysical contributions to radial velocities will become important for many (perhaps most) stars. The improved precision, combined with high-cadence observations will result in the detections of planets with

$M \sin i$ less than Neptune masses and with orbits up to approximately 1 year. Work in this area is just beginning and should reach fruition over the next 5–10 years. Other spectrometer designs (e.g., dispersed interferometers) have the potential for comparable performance, and perhaps higher efficiency. Observational programs are now starting and will test the performance and long-term stability of these designs.

Contributions to Navigator Science

Within the next 5 years, radial velocity measurements will push to lower mass limits ($\leq 5 M_{\oplus}$) and longer period planets (>15 years). The information on longer periods is particularly important in defining Solar System analogs with massive planets outside the habitable zone. The statistics of known planetary systems with giant planets similar to our own will provide an estimate of the number of habitable planets we should expect to find.

Transit Surveys

Current State of the Art

Observations of both photometric transits and radial velocity variations will play an important role in our understanding of exoplanets, for much the same reasons that eclipsing binaries are central to our understanding of stellar physics. If both observations are possible with individual planets, it becomes possible to estimate directly the planetary mass and radius, (hence density) and by inference, composition. Moreover, through the technique of transmission spectroscopy, transiting planets allow us a glimpse at the component we most desire to study, namely the atmosphere. The planet HD 209458b, illustrated in Fig. 7, exemplifies the dramatic impact of transiting planets on the field; the radius and mass of this planet are known with excellent precision, and both sodium and hydrogen absorption features have already been detected in its atmosphere. These detections were made by the Hubble Space Telescope, following up on the initial ground-based photometric detection.

As of September 2006, a total of 14 transiting planets had been detected: HD 209458b, HD 149026b, HD 189733b, OGLE-TR-10b, OGLE-TR-56b, OGLE-TR-113b, OGLE-TR-132b, OGLE-TR-111b, TrES-1b, TrES-2b, XO-1b, HAT-P-1b, WASP-1b, and WASP-2b. Three of these (HD 149026b, HD 20948b, and HD 189733b) had been previously discovered through radial velocity surveys. In early October 2006, two startling new results were announced. First,

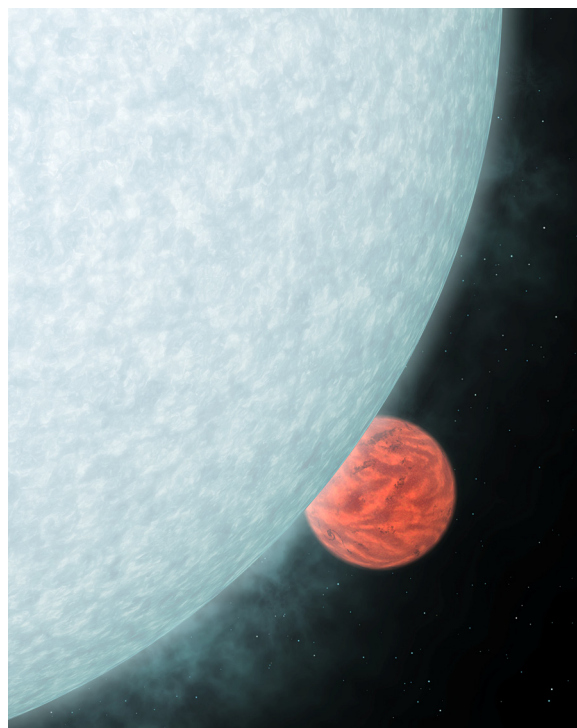


Figure 7. Artist's impression of the secondary transit of HD 209458b. Observations with the Spitzer Space Telescope detected the drop in infrared flux as the planet passed behind its host star. (NASA)

HST observations toward the Galactic center discovered an additional 16 candidate transiting planets, two of which are in sufficiently uncrowded fields to permit radial velocity measurements that have verified that they are indeed of planetary mass (Sahu *et al.* 2006). Second, Spitzer observations of υ And b throughout its orbit have shown that its star-facing side is about 1400 K hotter than its dark side; these observations demonstrate an extremely useful type of foreground-background observation, both because of its scientific value, which tells us something about the lack of atmospheric circulation, as well as its technical value as a new tool that can be exploited to characterize hot Jupiters. In 2006 transit and brightness-variation observations have rapidly gained ground as a valuable new tool for discovering and characterizing exoplanets.

Expected Near-Term Progress

More than 20 photometric surveys for transiting exoplanets are currently active. In the next few years, these surveys will likely detect even more gas-giant planets in short-period orbits (while terrestrial objects will remain well beyond the reach of these ground-based instruments). These surveys differ primarily in the typical brightness of the target stars. Many small-aperture, semi-robotic, dedicated wide-field transit surveys are now operational. These surveys will likely yield the greatest scientific impact for two reasons. First, the targets stars are sufficiently bright to permit an accurate determination of the star's radial velocity (and thus the planet's mass), to enable numerous follow-up studies of the planet's atmosphere, and to foster a search for additional bodies in the detected planetary systems through high-precision photometry and timing measurements. Second, transit searches typically require a long observing campaign to detect multiple transit events, and most large national or shared facilities are hard-pressed to accept this burden of telescope time.

Contributions to Navigator Science

The Canadian Space Agency's MOST project and the CNES's COROT project offer the prospect in the next few years of finding planets of a few Earth radii in short-period orbits through precision transit photometry. An observational knowledge of the frequency of Earth-sized objects even in such short orbits, combined with a comprehensive theoretical framework, will nonetheless improve the estimate of η_{\oplus} . On the slightly longer term, Kepler will extend COROT results to smaller-sized planets in orbits within a few tenths of an AU, and by 2012 Kepler will have directly measured statistics of Earth-like planets in the habitable zone if they prove to be common.

Microlensing Surveys

Gravitational microlensing events occur when a foreground object passes through the line-of-sight between a star and the Earth, producing a characteristic broad light curve, which may last several weeks. If the foreground object is a star with a planetary system, the broad light curve may include brief spikes in brightness that mark the passage of planets. Because these events are so rare, the observing strategy is to monitor large numbers of stars in regions of sky in the direction of the Galactic bulge. Fig. 8 shows the light curve deviation due to the planet OGLE-2005-BLG-390Lb, which, at $5.5_{-2.7}^{+5.5} M_{\oplus}$, has one of the lowest masses of any known exoplanet that does not orbit a pulsar.

The primary strength of the microlensing method is its sensitivity to planets of 1–10 Earth-masses at orbital distances of 1–10 AU, which corresponds to the vicinity of the Einstein radius. In contrast to other

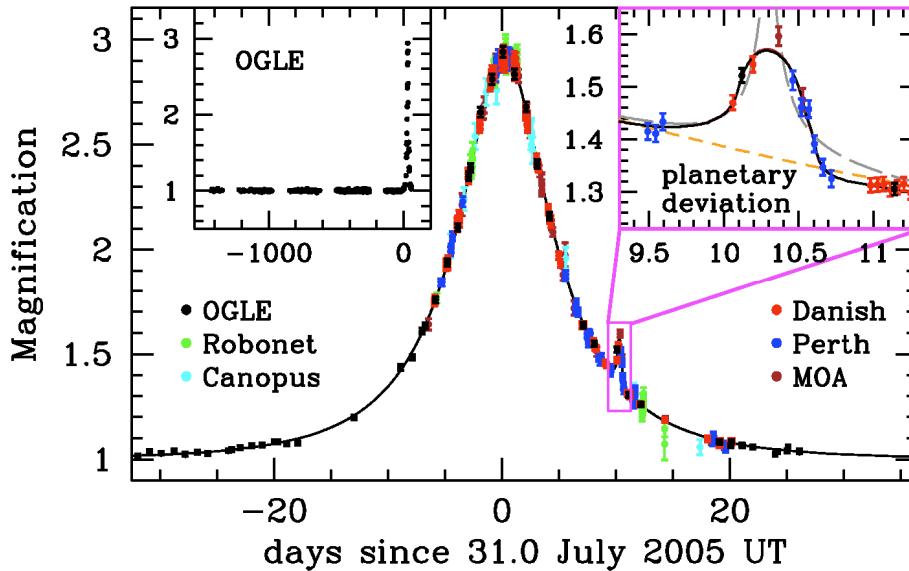


Figure 8. This light curves reveals the presence of a $5.5^{+5.5}_{-2.7}$ Earth-mass planet, OGLE-2005-BLG-390Lb, which is the lowest-mass planet yet discovered to orbit a normal star. It orbits an M-dwarf star located in the Galactic bulge with a mass $0.22^{+0.21}_{-0.11}$ solar masses at a separation of $2.6^{+1.5}_{-0.6}$ AU. In general, microlensing primarily targets M dwarfs, as they are the most common type of star. (Beaulieu *et al.* 2006)

exoplanet detection methods, the microlensing signals of low mass planets are not substantially weaker than the signals due to more massive planets. Instead of being weaker, the microlensing signals of low-mass planets have a shorter duration and require a more precise alignment between the source star and the lens star and planet. This means that if Jupiter-mass planets are as common as 10 Earth-mass planets, many more Jupiters should be detected. In fact, 2 of the 4 exoplanets discovered by the microlensing method have masses of ~ 10 Earth-masses despite the fact that microlensing is ~ 20 times more sensitive to Jupiters than to ~ 10 Earth-mass planets at separations of a few AU. The implied fraction of stars that have planets of ~ 10 Earth-masses at separations of a few AU is about 40%, with a 90% confidence-level lower limit of 16%. This implies that these planets are the most common type of exoplanet yet to be discovered.

Current State of the Art

The first microlensing surveys began observations in the early 1990s, but a serious attempt to find exoplanets did not start until 1995, with the creation of the Probing Lensing Anomalies NETWORK (PLANET) collaboration. However, the small number of microlensing events that were discovered by the microlensing survey teams limited the sensitivity of these early microlensing planet search programs. This, plus the small fraction of stars that have Jupiter-mass planets at a separation of a few AU, prevented any microlensing planet discoveries prior to 2002, when the OGLE-III wide-field-of-view camera came online. The OGLE-III project is able to discover ~ 500 microlensing events per year. This large number of events allowed the planet search teams to select the events to observe with the highest probability for a planet discovery. Subsequent improvements in observing strategy and prompt data sharing between the different microlensing teams have led to increasing planet-detection sensitivity in each of the subsequent years leading to one planet discovery from the 2003 season and three discoveries with 2005 data.

There are two current surveys, OGLE and MOA, and three follow-up programs (PLANET, the Microlensing Follow-Up Network (MicroFUN), and Robonet, which is affiliated with PLANET).

Expected Near-Term Progress

A significant increase in sensitivity is expected in 2006 and 2007 as the MOA II 1.8-m wide-field-of-view comes online in New Zealand, the Robonet's 2-m Faulkes South telescope is brought into full operation, and the 1.5-m telescope operated by PLANET at the Boyden Observatory comes into full-scale operation. The privately funded Las Cumbres Observatory Global Robotic Telescope may also make a substantial contribution to microlensing planet discoveries within a few years. This should provide additional detections of planets of ~ 10 Earth masses, and may enable the first discovery of an Earth-mass planet orbiting a normal star. The development of the microlensing method has been slowed by the fact that it involves a non-traditional observing mode that is only partially supported by traditional U.S. sources of support for astronomy. In fact, microlensing survey telescopes have only been funded by non-U.S. sources or by non-astronomy sources in the U.S. As a result of these difficulties, future investments in microlensing observing resources, such as a new wide-field-of-view 1.5–2-m telescope in South Africa is expected to have a particularly high payoff in terms of new low-mass planet discoveries.

Contributions to Navigator Science

Compared to other techniques, microlensing surveys provide more limited information about detected planets and their stars. The distance to typical targets makes microlensing targets the hardest to follow up using complementary methods. Nonetheless, microlensing has provided the first indication that planets of ~ 10 Earth-masses could be very common in orbits of a few AU, and is currently the only technique that has the ability to detect planets of an Earth-mass in orbits of several AU around main-sequence stars. Thus, microlensing provides our best chance to learn about η_{\oplus} before the Kepler mission is launched. A space-based microlensing mission would be sensitive to planets of a tenth of an Earth-mass at separations from 0.5 AU to infinity, including the habitable zone of main sequence F, G, and K stars. When added to Kepler results for close-in planets, a space-based microlensing mission would provide a complete statistical census of planets at all separations. These fundamental data on the properties of extrasolar planetary systems are crucial for understanding the planet formation process and the development of habitable planets. Such a mission would also further refine our knowledge of η_{\oplus} .

High-contrast Imaging

Current State of the Art

In recent years, there has been a vigorous growth in direct imaging planet search techniques from the ground. While none of these are expected to detect terrestrial planets, the search for Jovian planets in the outer regions of planetary systems will help to partially determine the architectures of the 93% of stars that do not (as yet) have radial-velocity planets. Ground-based programs also help to develop techniques and key technologies for Navigator missions. Many of these efforts have been fostered and encouraged through SIM Preparatory Science programs and TPF Foundation Science (see Appendix C).

High-contrast imaging includes techniques of direct imaging, coronagraphy, and methods of starlight suppression used with space telescopes (notably the Hubble Space Telescope) and with large ground-based telescopes equipped with adaptive optics. Because of the limited angular resolution of these systems, the detected planets have been in orbits 40 or more AU from the parent star. Moreover, the stars around which these planets orbit have so far *not* been main sequence stars. The first planet detected this way was a companion to the brown dwarf 2M1207, found by the Very Large Telescope (VLT) in 2004 and subsequently confirmed by HST observations. In 2005 a companion to GQ Lupi was announced, and an additional candidate, the substellar companion to the young star AB Pic A was also found (Chauvin *et al.* 2005). This was followed in 2006 by the discovery of a companion to SCR 1845-6357 (Biller *et al.* 2005). Figure 9 shows a coronagraphic image from the Lyot Project, illustrating the performance of this technique.

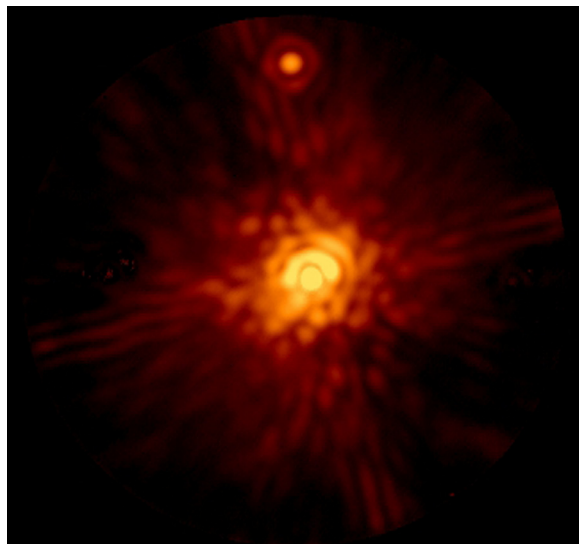


Figure 9. Coronagraphic image from the Lyot Project. A 15-minute H-band exposure showing a $M_H=11.4$ companion at 47 AU from an $M_H=1.39$ primary. (B. Oppenheimer, American Museum of Natural History)

For both ground and space techniques, the demonstrated performance limits are point-source detections at contrasts of ~ 10 mag at $r = 0.5$ arcsec. The key factor limiting performance is uncorrected wavefront errors due to the atmosphere or imperfect optics. Precision deformable mirrors with larger formats, improved wavefront sensors, and data analysis techniques to enable accurate subtraction of the residual stellar halo will be essential to overcoming this limitation, both on the ground and in space.

Expected Near-Term Progress

Both the VLT and Gemini observatories are funding the development of more advanced adaptive optics systems to achieve very high contrast close to bright stars (Goals of 10^6 to 10^7 contrast within 1 arcsec). The Gemini Planet Imager (GPI) in particular is fully funded through the NSF and is expected to come on-line in 2010. Not only will it help to discover potentially interesting solar systems for terrestrial planet searches, but it also shares several instrumental similarities with TPF-C, including apodized coronagraphic masks and an integral field spectrograph to suppress speckles from optical imperfections.

Additional direct detections of substellar companions and young (≤ 1 Gyr) or massive ($> 10 M_J$) brown dwarfs can be expected as surveys continue with ground-based adaptive optics. The HST experience has shown that space-based coronagraphy is capable of exploiting the stability of the instrumental point-spread function, and work is expected in the ongoing development of new mission concepts. A 2-m class space-based optical coronagraph could provide the first census of Jovian planets in the outer (> 5 AU) region of nearby stars, complementing the reflex motion planet searches, and yielding an improved estimate of the frequency and diversity of planetary systems. Such a new mission might also image hundreds of debris disks down to 10 zodi optical depths, resolving resonant structures that could indirectly indicate the presence of planets.

A separate but related avenue of high-contrast imaging is near-IR interferometry with large ground-based telescopes. The technique of differential-phase would use two 8- or 10-m class telescopes and measure fringe phase at two or more different wavelengths, thus being sensitive to different blackbody temperatures and able to sense the presence of a planet. Differential-phase interferometry is not a starlight-suppression technique, although the required system performance is nearly identical. (The technique of nulling interferometry is used for the characterization of exozodiacal dust and is discussed in the next chapter.) This method had been under development at JPL and could eventually be implemented to detect and characterize known hot gas giants around ~ 20 nearby stars.

Contributions to Navigator Science

Ground-based adaptive optics (AO) coronagraphs and interferometers using existing telescopes represent relatively modest investments that could return exciting scientific results on young or massive giant planets. A decade from now, new 30-m class ground-based telescopes, if equipped with high-performance AO systems, could begin direct detections of mature Jovian planets in reflected light. JWST, while not an optimized high-contrast imager, will be capable of imaging mature ($1 M_J$, 5 Gyr) Jovian companions to nearby late M stars, search for luminous exoplanets in young stars and studying the chemical evolution of circumstellar disk material.

Precision Astrometry

Current State of the Art

The current state of the art in ground-based CCD astrometry is defined by results from 4–5-m class telescopes. The astrometric signal amplitude from a Jupiter-mass planet around a solar-type star at 10 pc is ~ 0.5 mas. Several astrometric programs at meter-class telescopes have obtained ~ 1 mas accuracy in proper motion and parallax estimation, but they have not achieved the performance required to detect exoplanet signals with unknown orbital parameters. Long-term stability of < 1 mas has been demonstrated in a program that observes nearby M-dwarfs. M-dwarfs were selected because they are low-mass and faint, enhancing the signal and permitting nearby faint reference stars.

The current state of the art in small-field space-based astrometry is defined by measurements made with Fine Guidance Sensor 3 of the Hubble Space Telescope, capable of a small-field astrometric precision of 0.3 mas. Targeted measurements of Proxima Centauri and Barnard's star provided companion mass detection limits of $1 M_J$ for orbits with semi-major axes of 0.1–1.0 AU.

Expected Near-Term Progress

Improved astrometric measurements using single ground-based telescopes are possible with the use of larger apertures. Larger apertures provide improved averaging of turbulent atmospheric layers. Their greater light-collecting power allows a smaller field-of-view and narrower bandpass for detecting stars that define a reference frame. The turbulence-averaging and smaller field-of-view combine to reduce the relative motion of the target and reference stars, while the reduced bandpass improves differential chromatic refraction, the major systematic error. The observing time to achieve an astrometric noise level can easily be an order of magnitude smaller for a 5-m telescope than for a 1.5-m telescope at the same site.

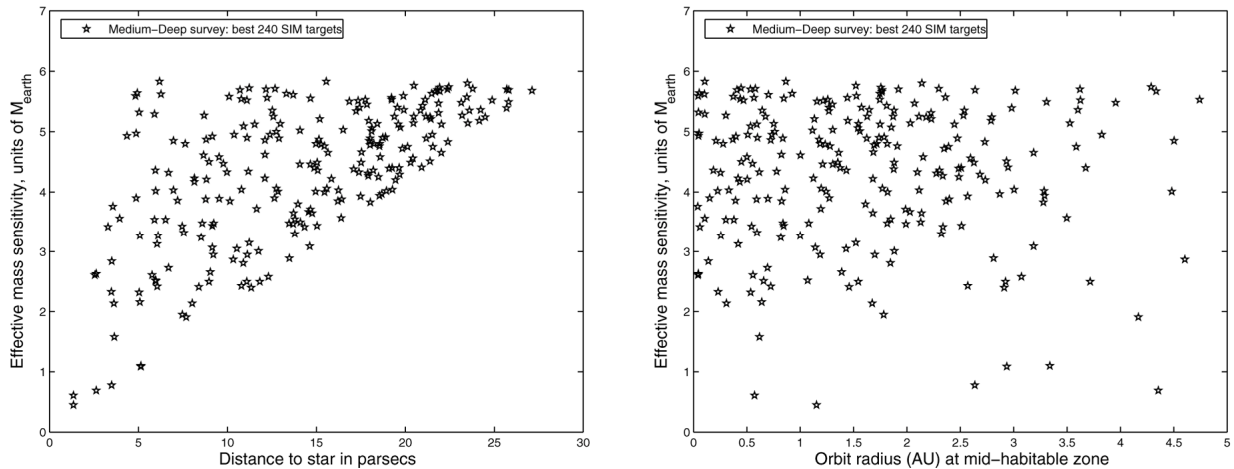


Figure 10. SIM PlanetQuest planet-mass detection sensitivity for individual target stars as a function of distance (left) and star-planet separation (right) for a medium-deep planet survey that includes 240 target stars. The single-measurement precision that is illustrated by both plots is $1.0 \mu\text{as}$ for a $V=7$ star. The effective mass sensitivity is for a 50% detection efficiency at a detection threshold corresponding to a 1% false-alarm probability. (Catanzarite *et al.* 2006)

Over the next few years, astrometry with ground-based interferometers should permit an order of magnitude improvement in ground-based, narrow-angle astrometric measurements with a precision approaching $20 \mu\text{as}$. In 1999 the Palomar Testbed Interferometer (PTI), located at a site with only modest seeing conditions, demonstrated a precision of $\sim 30 \mu\text{as}/h^{1/2}$ was possible using this technique. PTI required relatively bright ($K < 4.5$) and closed-spaced star pairs (< 30 arcsec), of which only two examples exist, so to observe a larger sample of stars an interferometer with larger telescopes is required; the Keck Interferometer was to be equipped with a small array of telescopes dedicated to this program, but this array is now unlikely to be deployed. A similar program at the VLTI (PRIMA) is nonetheless in development and its commissioning is expected to begin in 2007.

Interferometry from space will revolutionize the entire field of precision astrometry. SIM PlanetQuest will have a narrow angle precision of $1 \mu\text{as}$ in a single measurement, almost a factor of 100 better than currently available from the ground or with HST. As a pointed instrument, it will be able to observe much fainter targets than ground-based interferometers, which are expected to reach about $20 \mu\text{as}$ precision.

Contributions to Navigator Science

The astrometric approach to planet detection is complementary to the radial-velocity technique. Whereas radial velocity and transit surveys are most sensitive to massive planets with close-in orbits (causing detectable radial velocity shifts), astrometric surveys are more sensitive to planets with wider orbits (providing a measurable astrometric signal) and also have a lower detectable mass limit. In this way, astrometric surveys may be better suited in the long term to detecting planetary systems similar to our own.

Ground-based astrometric interferometers, such as KI and VLTI, are important for detecting and determining the masses of long-period gas-giant planets around Navigator target stars. Only such facilities

can produce the long time baseline of observations needed to determine orbits at or beyond the distance of Saturn with its 30-year period.

SIM is one of the most important precursor missions for TPF. SIM will provide a comprehensive survey of all likely TPF target stars: SIM has three approved key projects to perform astrometric searches for planets around nearby stars. The SIM target list will be a super-set of the entire TPF list. The scientific implication is profound: for every TPF target, we will know what planetary-mass bodies each system contains, for periods less than about 10 years and masses down to a few Earth masses or smaller. Radial velocity measurements are complementary to SIM, i.e., for long-period planets, SIM fills in the search space for which radial velocity measurements are unable to detect even Jupiter-size planets. The two most important scientific results from SIM are the following:

1. *Measurement of planet masses:* Except for microlensing (which finds planets orbiting stars that are too distant to be TPF targets), and planets detected by radial velocity and transits, only SIM measures mass directly. Mass is the most fundamental property of an astronomical body. Knowing the masses of planets, when found, in systems around TPF targets is vital information to understanding the significance and the context of any TPF-detected terrestrial planets. The ability of SIM to detect planets of various masses is illustrated in Fig. 10.
2. *Measurement of orbital elements:* Radial velocity measurements cannot yield full knowledge of planet orbit and phase, crucial for efficiently scheduling observations with a TPF mission. Current radial velocity sensitivity cannot detect Earth-sized planets in the habitable zone. SIM's ability to detect these planets and characterize their orbits will greatly aid in identifying planets that reside inside, or spend a significant fraction of their orbit within, the habitable zone of a star.

SIM will screen the TPF target list. Since SIM will be capable of detecting planets in the range of mass and orbit radius of interest to TPF, it can serve to identify good and bad targets — or at least assist in the priority order for observation. SIM will identify the targets to avoid, for example systems where there are one or more giant planets in the habitable zone. Although these targets will be of high scientific interest, it is unlikely that they would harbor habitable worlds for TPF to investigate. SIM will also identify high-priority targets, those for which terrestrial planets have already been detected. If such planets are common, then SIM should detect at least a few that also lie in the habitable zone around their parent stars. There will also be potential targets — those in which SIM finds either no planets at all, or massive planets in orbits which permit stable orbits in the habitable zone. For our Solar System, this would be equivalent to detecting Jupiter and Saturn, then (correctly) inferring that the Sun is a good target star for a terrestrial planet search.

TPF will mine the SIM data archive. SIM will likely yield several marginal detections for every positive detection. A joint solution for orbital elements using SIM and TPF data would allow masses and orbits to be derived for many more planets; roughly a factor of two improvement in the SIM mass limit can be expected.

If complex planetary systems prove to be the norm, then it will be more challenging for SIM to determine the orbits for planets within each system. However, an extended mission of up to 10 years and monitoring by ground-based astrometric interferometers over longer periods should resolve ambiguities in the data.

3.3 Theory and Modeling

A quantitative and testable theory of planet formation is the essential conceptual basis of searches for exoplanets. Considerable new insights in planetary formation within protostellar disks have been gained in the past few years as the discovery of exoplanets has widened our horizon. New theoretical models will allow us to predict and to confront the observable statistical properties of newly found exoplanets and the diversity of planetary systems. For the TPF preparatory science program, a concerted theoretical program to understand the detailed process of planetary formation is particularly relevant to paving the path for TPF's central mission.

Protostellar Disk Formation

Today, the most basic construct of planet-formation theories remains similar to Laplace's nebula hypothesis, in which planets and their host stars are assumed to form concurrently, with the former in gaseous disks surrounding the latter. New quantitative models of the solar nebula and rigorous theories of accretion disks have been developed recently to study the structure, stability, and evolution of protostellar disks. However, there are numerous paradoxes in the current theoretical models that must be resolved before a comprehensive and statistically deterministic theory of planet formation can be constructed that is both compatible with the most crucial existing observations and has predictive powers to guide future missions.

Current theoretical studies of the structure and evolution of protostellar disks need to be continued and expanded so that the physical conditions and the persistent time scale of nascent disks can be more accurately defined. Theoretical investigations are needed to identify the processes that determine the retention efficiency of heavy elements in planets, formation probability of planets, and growth time scale of planetesimals. Special efforts should be made to identify observable signatures of planetesimals' growth in their nascent disk environment. Observations of the dust-and-gas phase transition, the grain-size distribution, the evolution of protostellar and debris disks, and the metallicity of their host stars will be mutually beneficial and fruitful. Theoretical efforts toward improving our knowledge of protostellar disk models should provide a variety of plausible boundary conditions to delineate the time-scale, efficiency, and outcome of planet formation.

Planetesimal Formation

A necessary step in the formation of terrestrial planets is the formation of planetesimals. At present, very little is known of how they form, under what conditions, and with what efficiency. Does metallicity need to be high? Do chondrules need to form first? What range of nebula turbulence is compatible with forming planetesimals? Further research is needed to be able to predict with what frequency planetesimals are formed from circumstellar disks, and this in turn will set a theoretical upper limit on the frequency of Earths. Knowing the efficiency of conversion of dust to planetesimals helps to establish whether a system contains Neptune-like planets at 1 AU, Earth-like planets, or Moon-sized objects.

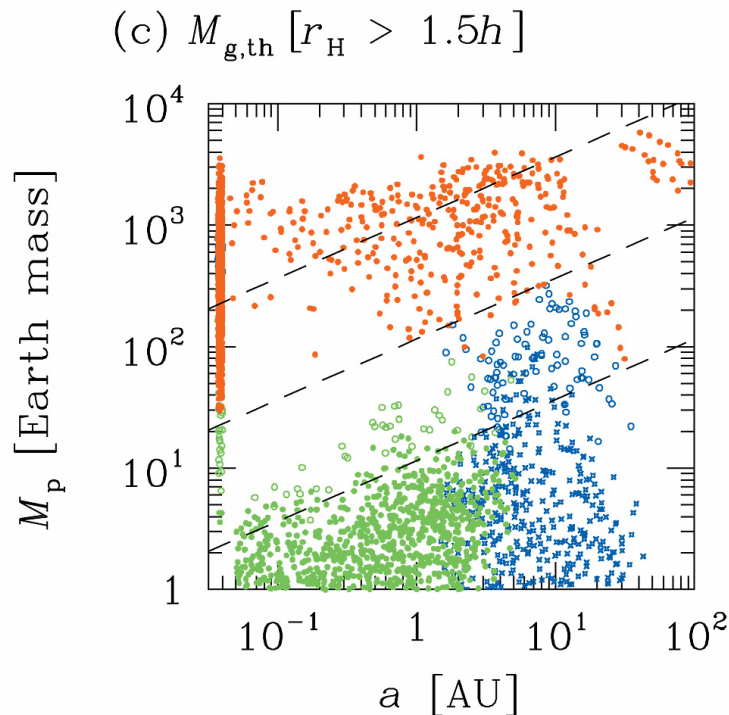


Figure 11. Results of simulations of 3000 planets evolved from simulated initial protoplanetary disks. The various types of resulting planets are highlighted. The blue and green *filled* shapes denote planets whose gas mass is less than its solid mass. The *open* blue squares and green triangles denote planets whose gas mass is less than 10 times their solid core mass. The filled red circles denote planets whose gas mass is greater than 10 times their solid core mass. (Ida and Lin 2004)

Asteroid-Belt Formation

Asteroids are a promising source of volatiles for terrestrial planets, and their frequency has important consequences to the formation of atmospheres and hydrospheres, and therefore to planetary characterization. Theoretical work is needed to predict the formation of asteroids and asteroid belts which are likely to occur in planetary systems. How do giant planets influence whether planetesimals lead to terrestrial planets or asteroids? Where in the disk will each class of object form? If the habitable zones of most stars contain asteroids rather than planets, then Earth-like planets may be rare amongst our nearest stars.

Terrestrial Planet Formation

Generalizations of the theories of planet building are needed in order to assess the formation probability of individual terrestrial planets around stars with different masses, progenitor clouds, protostellar disks, metallicities, and formation environments (such as O-B associations or clusters). Preserved crater scars on Mercury, the Moon, and asteroids are strong indications that they were formed through cohesive collisions of smaller building blocks. Despite the conceptual simplicity of this model, the details of the growth from dust to planetesimals, protoplanetary embryos, and cores are not yet well understood. The craters that are now seen were produced by relatively small impacts compared with the size of the present moons and

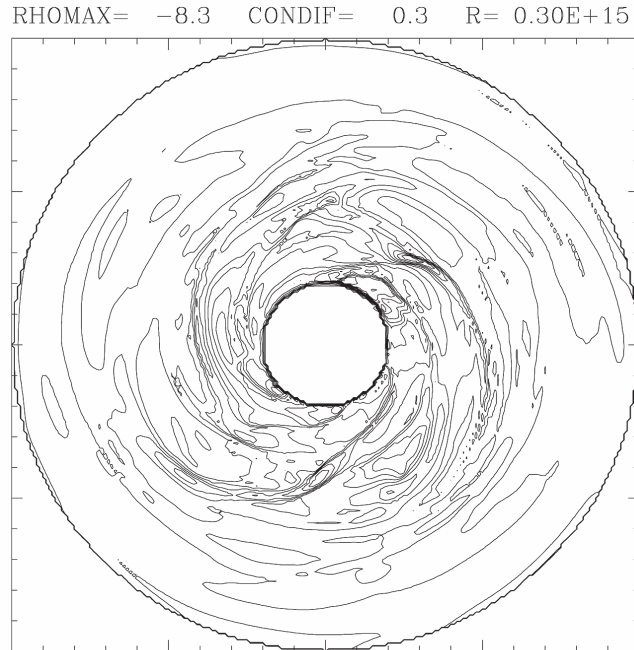


Figure 12. Simulation of giant planet formation from a gravitationally unstable disk. One epoch of a time-series of simulations is shown illustrating the formation of spiral arms in the disk, leading eventually to the formation of self-gravitating giant planets. (Boss 2005)

planets, and much of the history of planet-building remains based on conjecture. Most of the current theories and models of terrestrial planet formation are still based on the dynamics and meteoritic data of our own Solar System.

Improved computer simulations and statistical modeling of planetary growth are needed over a wide spatial and temporal range to understand the processes that determine the magnitude of the dynamical filling factors of planetary systems. An example of such work (Ida and Lin 2004) is shown in Fig. 11. Similar studies have been undertaken by other authors (e.g., Chambers 2001, Benz *et al.* 2006, and Raymond *et al.* 2006). The dynamical filling factor of the planetary embryos and residual protoplanets determines the capacity of any planetary system to bear Earth-size habitable planets. This factor regulates not only the planets' collision and growth rates, but also their orbital stability and evolution. These investigations are necessary for establishing the circumstances (e.g., orderly versus runaway coagulation) that may produce planetary systems with high dynamical filling factors, as well as those (e.g., strong perturbations from giant planets) that may quench terrestrial-planet formation and lead to dynamically sparse planetary systems. Theoretical investigation is also needed to identify the determining factors in the difference in the mass of the atmospheres of terrestrial and giant planets.

Giant-Planet Formation

It is important to carry out numerical simulations of various physical processes that determine the mass-distribution and orbital properties of Jupiter-mass planets. The two main classes of theories suggest that giant planets are either formed through core-nucleated accretion, shown in Fig. 11, or gravitational instability, shown in Fig. 12. Although both models have their validities and represent circumstances that might occur in nature, we need to assess their actual probability and to work out their implications:

1. The core-nucleated scenario requires the formation of several M_{\oplus} terrestrial-planet-size cores prior to their gas accretion such that the coexistence of terrestrial and gas-giant planets is naturally assumed. However, core-accretion theories have been plagued by a growth-barrier and formation-time-scale paradoxes.
2. It is still unclear whether gravitational instability gives rise to planet formation, or instead simply results in changes in the structure of the disk.

If, as core-accretion models would suggest, the formation of giant planets and 10-Earth-mass planets are associated with planetesimals, then observations tell us that planetesimals form around ~40% or more of stars. Do giant planets form independently or in conjunction with terrestrial planets? How often? In what part of the disk? What are the timescales for formation? If giants tend to form on highly eccentric orbits, or within about 3 AU, or in multiple-planet systems with anything but low eccentricities, then terrestrial planets may not form due to giant-planet perturbations. The nature of giant-planet formation will strongly affect the delivery of volatiles to terrestrial planets.

Further theoretical analyses are needed to determine, under various possible conditions, the evolution of the rocky cores thought to exist within Jupiter, Saturn, Uranus, and Neptune. Studies of exoplanets by transit photometry, summarized in Fig. 13, have yielded the mass-radius relationship of a small sample of giant planets. Present among these are giant planets with surprisingly tenuous atmospheres. The presence of rocky cores, however, is generally interpreted as evidence for the emergence of terrestrial planets. The inference from the giant planets' structure to the potential coexistence of terrestrial planets needs a better theoretical understanding of the growth and survival of cores due to gas accretion, rapid envelope rotation, giant impacts, and intense tidal heating.

Departures from what we might expect from direct accretion from the nebula provide important clues to the formation and evolution history of a planet. Giant planets serve as an archive of the history of a planetary system and provide insight into the volatiles that may or may not have been delivered into the habitable zone. The issue of volatile delivery is still controversial when applied to the history of our own Solar System. The near-uniform enrichment of volatile heavy elements in the atmosphere of Jupiter has been interpreted as evidence that planetesimals bombarded the atmosphere over time. Future observations will determine if most extrasolar giant planets are enriched in atmospheric heavy elements above the amount in the atmosphere of their primary stars. If observed, not only would such enhancements provide insight into the delivery of volatiles to giant planets, but also to terrestrial planets in the habitable zone. It is therefore important to arrive at more sophisticated models of giant planet atmospheres to be better able to interpret the observed spectra.

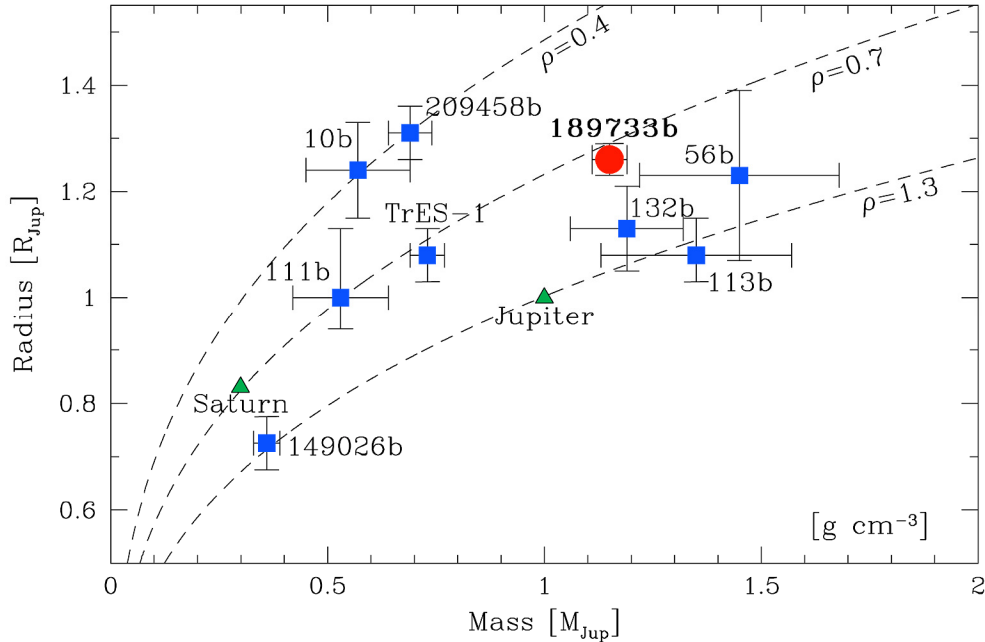


Figure 13. Mass-radius relationship for the first 9 detected transiting planets. The curves that indicate a constant density (0.4, 0.7, and 1.3) show that many of the gas giants detected so far could have a composition similar to Jupiter or Saturn (indicated by the triangles). However, the existing sample includes gas giants that must have a very tenuous atmosphere; intermediate in mass between Saturn and Jupiter, but with about half the density of Saturn. (Bouchy *et al.* 2005).

Orbital Stability

Theoretical investigation is needed to assess the persistence of terrestrial planets and to determine the range of survivable dynamical filling-factors in habitable zones. During post-formation evolution, gravitational perturbation between planets can strongly alter their initial kinematic properties. Under their mutual gravitational perturbation, terrestrial-planet properties (such as semi-major axis, eccentricity, and obliquity) may evolve. This evolution process may become more active in systems with larger dynamical filling factors. The application of gravitational perturbation is directly relevant for the determination of possible eccentricity, inclination, stability, and survivability of terrestrial planets in habitable zones around host stars with previously discovered gaseous giant planets. Orbital modulations may be important for the emergence of life on these planets. It may be true that terrestrial planets are rare among the stars with known Jupiter-mass giant planets: celestial mechanics of the Solar System indicates that the orbits of terrestrial planets may be strongly perturbed by their gravitational interaction with the more massive giant planets, and many exoplanets have larger mass, greater eccentricity, and smaller semi-major axes than Jupiter. Therefore gravitational perturbations induced by them are likely to be more intense.

Theoretical models are essential for the assessment of the orbital stability and evolution of multiple-planet systems. These calculations include the perturbation of the terrestrial planets on the orbit of gas-giant planets. Furthermore, self-consistent models are needed to establish the orbital configurations of mutually

interacting planets around common host stars. In the current search for terrestrial planets, numerical computation is essential for extracting dynamical information from radial velocity and astrometry data.

Planetary Migration

The discovery of extrasolar giant planets in orbits close-in to their parent stars has forced a major revision of theories of planet formation. Since it seems unlikely that gas giants could form close to their parent stars, they are thought to have formed at much greater distances and then migrated to their present orbits.

In type I migration, the planet does not clear a gap in the disk from which it forms, but changes its orbit due to the torques generated by the wakes it creates in the surrounding disk. In type II migration, a newly formed large planet opens a gap in the circumstellar disk and subsequently evolves with it. The statistics of planetary migration have important consequences for the frequency of Earths. As giant planets migrate, so do their unstable resonances, and resonance sweeping may remove terrestrial planets from many systems in which they form. If gas giants commonly migrate through the terrestrial region in the disk lifetime, terrestrial planets may rarely form. Under what conditions are type I and type II migration effective? What are the migration timescales? At what stage in the disk lifetime can this occur?

It will be useful to identify the effect of gas-giant planets' orbital migration and eccentricity excitation on the emergence of terrestrial planets in habitable zones. Orbital migrations can lead to resonant capture, divergent orbital evolution, and dynamical instability among some known multiple gas giant planetary systems. The extension of these theoretical studies to terrestrial planets will determine their post-formation migration, depletion, and resurgence in the habitable zone. An extrapolation of the migration theory and inference on the possible existence of hot Earths, in systems with or without hot gas giants, will help to establish the terrestrial-planet-formation efficiency with transit searches.

Theoretical analyses are needed to understand the effects of dynamical perturbation by either emerging or pre-existing giant planets on the formation environment, process, and orbital stability of terrestrial planets. A related issue is whether the spatial segregation of terrestrial and giant planets is universal or unique to the Solar System. Theoretical investigation is also needed to identify if the formation of one giant planet may promote and enhance the subsequent formation of other giant planets, as perhaps indicated by radial velocity surveys. It will be important to understand as well if the emergence of Jupiter may have suppressed the formation of modest-sized, let alone giant planets, in the region of the asteroid belt.

From Gas Giants to Earth-Like Planets

Theoretical predictions of the frequency of Earths are tied to the mechanisms by which gas-giant planet formation occurs, as gas-giant planets dominate the dynamical evolution of smaller bodies in their vicinities. Hence it is important to understand how and when gas giants form. There are two competing theories of gas giant formation, core accretion and disk instability. Core accretion requires several million years or more to form a gas-giant planet, while disk instability requires much less time. If disk instability is able to form gas giants, then the gravitational perturbations from Jupiter-mass planets will be present throughout the phase when planets are trying to form. Simulations to date imply that having a rapidly formed Jupiter can increase the chances for the formation of a Earth-mass planet on a habitable zone orbit,

Table 4. Summary of Ongoing Theory and Modeling Programs Relevant to the Estimation of the Frequency of Earths

Science Program	Science Objectives
Frequency of exoplanet formation	Understand the physical conditions for planet formation, timescales, efficiency of planet formation, and barriers to planet formation.
Evolution of planetary configuration	Predict the evolution of planetary systems using dynamical modeling for the period after planet formation. Predict the possible dynamical filling factors.
Terrestrial planets in the presence of giant planets	Model and predict the formation and preservation of terrestrial planets in the presence of known giant planets.
Understanding the formation of terrestrial planets	Understand the growth from dust to km-size objects and barriers to growth. Confront theoretical predictions with known measurements and predict the frequency of terrestrial planets and exozodiacal dust levels.
Thermal evolution of planets	Understand the evolution of the interiors and atmospheres of terrestrial planets. Understand the differentiation of materials and the coupling between atmosphere and surface physical processes.
Observation and modeling archive	Provide an archive of information on the search for planets — for both observers and theoreticians.

because the giant planet’s gravity hastens increases in orbital eccentricities of the planetary embryos that are needed in order for these embryos to collide and produce Earth-mass planets. In either scenario of gas giant planet formation, Earth-like planets must form by the slow process of collisional accumulation of progressively larger solid bodies, which requires tens of millions of years to run to completion.

We can apply theoretical models to analyze the observed properties of gas-giant planets and extrapolate the efficiency of Earth formation. Projecting from the success of the past 11 years, we can anticipate the discovery of a large number of new planets from which to base our predictions. This new data will provide input to theoretical models with which we can extrapolate the production rate of Earths. For stars with no known gas-giant planets, stringent upper mass limits of undetected planets for a range of periods can also provide constraints on planet-formation theories.

3.4 Summary: Opportunities, Risk, and Priorities

Recommendations

On the timescale of TPF-C and TPF-I, it is unlikely that any other missions will directly detect light from a terrestrial planet. Our current knowledge of terrestrial planets is limited to our own Solar System and to the six exoplanets known to be less than about 10 Earth masses. Of the six, three were detected by pulsar timing, two by radial-velocity techniques, and one by microlensing. An improved understanding of the atmospheric composition, formation, and evolution of giant planets is essential to a complete picture of how terrestrial planets form, and whether their orbits are stable over long timescales. For gas-giant planets, surveys using radial velocity, astrometry, stellar transits, and microlensing techniques offer possibilities of increasing our understanding of extrasolar planetary systems. Of these techniques, the ones most likely to make a significant contribution to TPF are the radial velocity surveys, microlensing, and space-based transit missions.

Recommendations relevant to the approaches that have been outlined above can be summarized as follows:

- *Microlensing surveys* have proven their sensitivity to low-mass planets and will probably provide the best estimate of η_{\oplus} from ground-based observations. However, microlensing planet detection requires a very large number of photometric measurements from telescopes at multiple longitudes, and this is an observing mode that is not generally provided by funding agencies such as the NSF or by large private observatories. The Las Cumbres Observatory Global Robotic Telescope may help to fill some of the gap in observing resources, but a 1.5–2-m wide field-of-view telescope in South Africa is a very high priority that should substantially increase the discovery rate of exoplanets in the 1–10 Earth-mass range.
- *Radial velocity monitoring* is a proven technique that will yield more long-period planets as the time-baseline of observations continues to increase. There is a shortage of high-resolution échelle spectrometers for radial velocity survey work. These instruments are currently oversubscribed with planet searches and efforts to cull binaries for reference stars and grid stars for interferometry. New spectrometers represent significant upgrades for existing, under-used 2–3-m class telescopes. This may have the added advantage of shifting the research load on larger telescopes to work that is uniquely possible with a larger aperture. Surveys conducted by robotic telescopes in remote sites with excellent seeing also represent a good investment as workhorses for exoplanet detection.
- *Ground-based transit surveys* for gas-giant planets should be further encouraged; this technique is still not fully exploited. In particular, the potential of a robust, worldwide network of dedicated wide-field transit-search telescopes should be investigated since the follow-up studies enabled by these bright targets are very exciting.
- *High-contrast imaging surveys* for brown dwarf and giant-planet companions have the potential to inventory the major bodies in the outer (> 5 AU) region of nearby planetary systems, without waiting for a full orbital period to elapse. Such investigations can provide the full picture of the end products of planet formation in general, and for the TPF target stars in particular. Development of specialized wavefront sensing and control instrumentation is needed to advance both ground and space telescopes to the required contrast performance limits.
- *A comprehensive theoretical investigation* into many aspects of the formation and evolution of planets and planetary systems must provide the framework within which to understand the necessarily incomplete observational results. Examples of such investigations are listed in Table 4. The combination of the existing near-term radial velocity and transit programs with theoretical insights into orbital stability, planetary migration, and the relationship between gas giants and rocky planets will give us the confidence to move forward with TPF.
- *Prior to SIM PlanetQuest, other techniques* such as ground-based astrometry, contribute to the overall picture. Each technique has particular advantages. The synthesis of all these techniques within a broad theoretical framework is critical to appropriate development of TPF-C and TPF-I and subsequent interpretation of data from the missions.

Perhaps the greatest risk to improving our understanding of extrasolar planetary systems would be the failure of the Kepler mission to be launched successfully or for it to perform at less than expected levels. In

this case, TPF-C would not benefit from improved statistics of terrestrial planets prior to entering Phase B/C/D. Mitigating against this risk will be the microlensing discoveries of planets in the 1–10 Earth-mass range at orbital separations of a few AU and continuing progress in making radial velocity measurements to more precise levels and on longer temporal baselines. By 2010, radial velocity measurements will be able to detect planets as small as 5–10 Earth masses inside 0.5 AU, enough to give stronger support for theoretical estimates of η_{\oplus} . COROT may detect large terrestrial planets around M stars if η_{\oplus} is sufficiently high (>0.1) although this will be challenging around hotter stars.

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4 Exozodiacal Dust

4.1 Objectives of Precursor Science

Relevance to the Navigator Program

Exozodiacal dust is of major importance to building a better understanding of the formation and evolution of planetary systems. However, for planet detection, exozodiacal emission can be a bright background that TPF-C and TPF-I must overcome in searching for planetary signals. Both the mid-infrared interferometer and the visible coronagraph architectures are affected by the presence of dust emission. A more complete understanding is, therefore, of great importance prior to the earliest mission concept review.

Metrics for Decision Making

The advantage of coronagraphs versus interferometers depends on exozodiacal light levels and the distance to the individual targets, and will be assessed in greater detail in the ongoing trade studies. The effect of increased levels of exozodiacal emission is to increase the integration time needed to detect a planet. The performance of both coronagraphs and interferometers degrades as the level of exozodiacal light and the distance to the star increases. However, below about 10 times the Solar-System levels, the observing-time penalty is not severe — an increase of a factor of up to 3.5. If it were found that most potential target stars had levels of exozodiacal light much greater than 10 times the Solar-System level, longer integration times would need to be accounted for in the mission design.

Schedule and Deliverables

In Pre-Phase A, the mission concept review — assessing technological readiness of the coronagraph or interferometer designs — is the highest priority issue that must be addressed. Thus, a fundamental question to be resolved prior to the review is to determine the number of stars that are likely to have exozodiacal levels less than 10 times those of our Solar System. A preliminary target list is also needed, along with exozodiacal light measurements or limits for each target. Such measurements are needed about a year before TPF-C enters Phase A. This will allow the information to contribute to the mission concept review in a timely manner.

Properties of Protoplanetary Disks

Stars form through the collapse of dense cores in interstellar molecular clouds. During this process, angular momentum conservation dictates that a rotating disk of gas and dust form around the young star. Planets form in this circumstellar disk, interact with it, and implant their signatures on it. The discovery of such disks around nearby stars (Backman *et al.* 1986) has provided the opportunity to study planet formation in real time, and to observe processes that may have operated in the young Solar System. They are also important for the detection and characterization of terrestrial planets, since circumstellar dust has been detected around stars that are billions of years old (e.g., Beichman *et al.* 2005) and is present in the Solar System today (the zodiacal dust). Exozodiacal dust is a source of background flux that must be considered in any effort to image terrestrial planets. Studies of exozodiacal dust may also provide indirect evidence of planets through structure in the dust disk caused by gravitational perturbations; the signature of the Earth may be seen in clumps in the zodiacal dust of the inner Solar System. Finally, the composition of dust and gas in older circumstellar disks should reflect the composition of extrasolar planetesimals, which may provide insight on the diversity of terrestrial planets and their atmospheres.

The main phases in the formation of a planetary system like our own are the formation of gas-giant planets like Jupiter, the formation of terrestrial planets, and the clearing of most of the leftover planetesimals from the system. This timeline is represented in Figure 14. It is during the last phase that most of the volatile content of Earth's surface was delivered by the impact of water-rich asteroids and comets (e.g., Morbidelli *et al.* 2000).

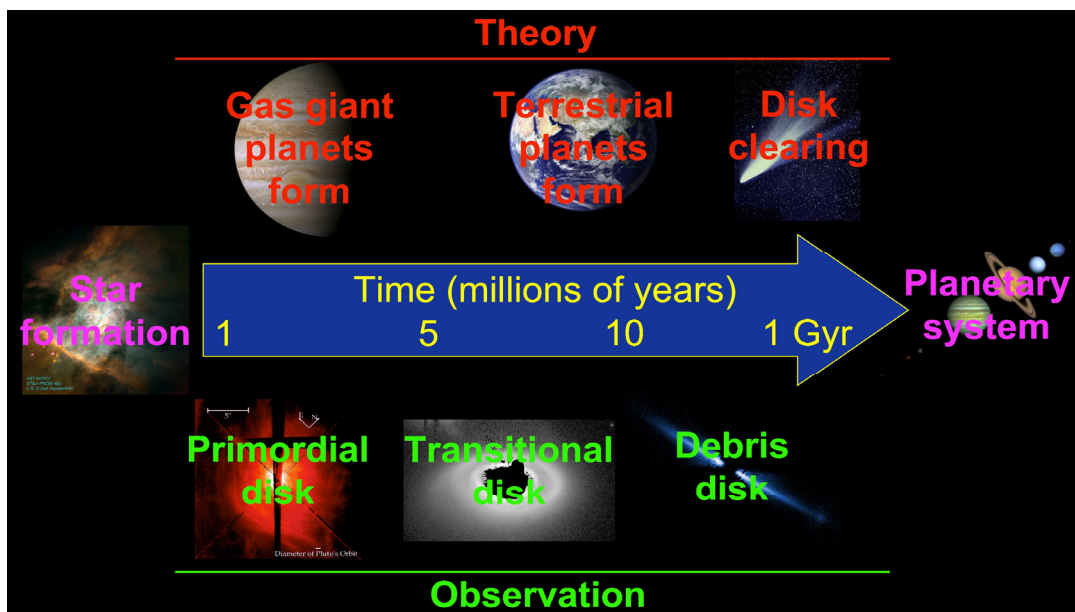


Figure 14. The current timelines for planet formation and the evolution of circumstellar disks. Above the arrow, the main theoretical phases in planetary formation are shown. Below, the classes of circumstellar disks are identified. A coronagraphic image of an example from each class is shown; the primordial disk around AB Aurigae at left (Grady *et al.* 1999), the transitional disk around HD 141569A in the center (Clampin *et al.* 2003), and the debris disk around AU Microscopii at right (Krist *et al.* 2005). (Figure by A. Roberge, Goddard Space Flight Center)

Protoplanetary disks are currently divided into three classes. The youngest class is the primordial disks, which are composed of relatively unprocessed interstellar material left over from star formation, and should correspond to the solar nebula. Primordial disks are gas-rich, as evidenced by observations of CO emission (e.g., Raman *et al.* 2006); the bulk of the gas, however, is molecular hydrogen. The composition of a primordial disk should resemble that of an interstellar molecular cloud, with a gas-to-dust ratio near 100:1. Since giant planets are primarily composed of gas, they must form in gas-rich disks, and the primordial disks match this description.

The oldest class is the debris disks, which are dusty, gas-poor disks. These disks are composed of material produced by the destruction of planetesimals, through collisions and evaporation. Debris disks have a wide range of ages, from about 10 Myr to a few Gyr. Terrestrial planets are likely forming in the younger debris disks, while the older ones correspond to the disk-clearing phase during which many leftover planetesimals are removed from the system. Dust is removed from debris disks through Poynting-Robinson drag, planetary sweeping, or radiation pressure. In these disks, the dust must be replenished via planetesimal collisions instigated by larger planetary bodies. Transitional disks occur between these two classes of disks and have some of the characteristics of both. Coronagraphic images of a disk from each of the three classes are shown in Figure 14. Figure 14 implies a very clean, orderly progression in both planet formation and

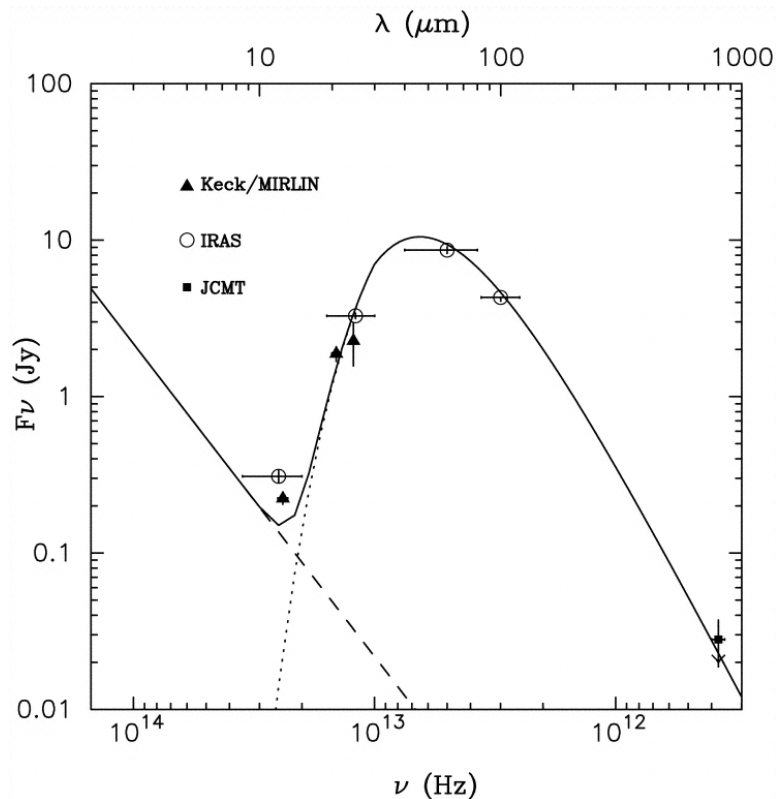


Figure 15. Spectral energy distribution of HR 4796A. The points show photometry of the system from *IRAS*, the JCMT, and the Keck Telescope. The dashed line shows the expected flux from the central star. The dotted line shows the best-fitting dust emission model, which is a disk extending from 55 AU to 80 AU. The solid line shows the sum of the flux from the star and the modeled dust emission. (Koerner *et al.* 1998).

disk evolution. However, the theoretical stages in planet formation may be occurring simultaneously in different parts of a disk. In addition, the different classes of disk are not cleanly separated, with apparent overlap in the age ranges of each class.

This chapter will discuss areas of active observational and theoretical progress and outstanding problems in protoplanetary disk studies. The interactions between planets and their neighborhoods will be discussed, as well as the impact of exozodiacal dust on imaging and characterization of exoplanets in the habitable zones around other stars.

4.2 Observational Programs

The next few years will yield significant progress on the abundance, composition, and morphology of exozodiacal emission around nearby stars. Using photometry, spectroscopy, direct imaging, and interferometric observations, the formation and evolution of debris disks, their relationship to planetary systems, and their detectability will be explored.

Photometry

Disks are typically first detected by observation of infrared to millimeter-wavelength emission in excess of that expected from the central star. This emission is produced when circumstellar dust absorbs emission from the star and re-emits it at longer wavelengths. Models of the dust emission may be fit to the spectral energy distribution (SED) of the system, providing an estimate of the fractional infrared luminosity (L_{IR}/L_*) and the effective dust temperature, the combination of which can yield the dust mass. An example of an SED with large infrared excess from a debris disk is shown in Figure 15.

The most important current mission for the detection and characterization of infrared excesses around solar-like stars is the Spitzer Space Telescope. Spitzer is capable of making sensitive measurements of exozodiacal clouds at wavelengths of 24 μm , 70 μm , and 160 μm , spanning typical temperature ranges of 40–200 K and corresponding to distance scales of a few to a few hundred AU from the parent star. The sensitivity to exozodiacal emission is limited by Spitzer's photometric accuracy of a few percent at 24 μm and 7–15% at 70 and 160 μm , allowing Spitzer to detect or set limits on excesses that are less than 10–50% above the stellar photosphere.

At 24 μm , this limit corresponds to a factor of 100 to 500 times the level of dust emission in our own Solar System in the distance range of 1 to 10 AU, where 100–200 K dust is located for a solar type star. At longer wavelengths, the photosphere is weaker, and the corresponding limit is 30–100 times the level of dust in our Solar System between 10–100 AU (\sim 50 K dust). Spitzer has already observed or has awarded time for observations of over 200 likely Terrestrial Planet Finder (TPF) target stars.

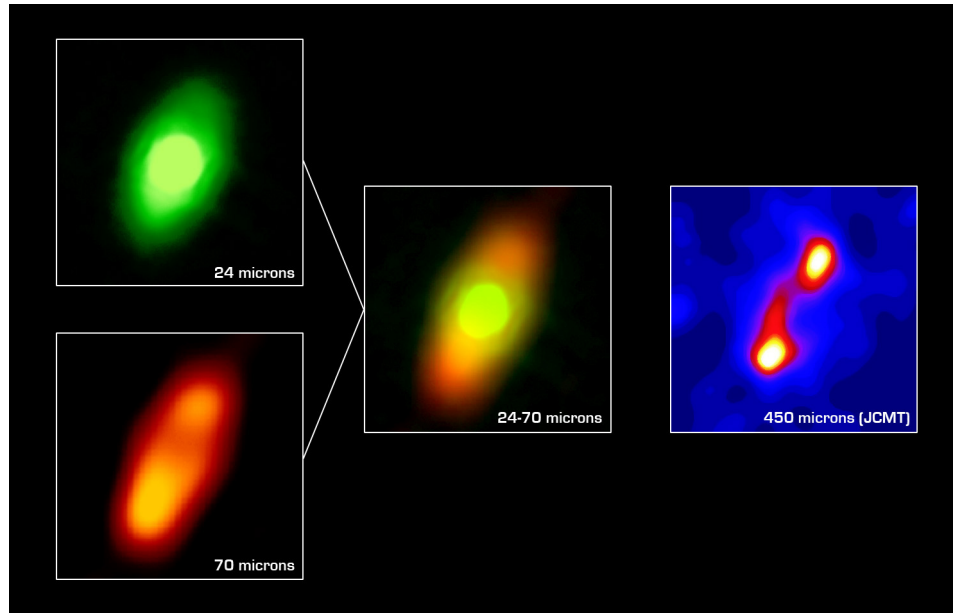


Figure 16. Image of the dust disk around Fomalhaut, taken with the multiband imaging photometer of the Spitzer Space Telescope. The 70- μm image (lower left) clearly shows an asymmetry in the dust distribution, possibly due to collisions between asteroids. At 24 μm (upper left), the center of the ring is shown to be not entirely empty. This warm inner disk is analogous to our own zodiacal cloud, but with considerably more dust. (K. Stapelfeldt, JPL)

Disk Imaging

Spectral Energy Distribution (SED) fitting can provide some information on the spatial distribution of the dust (for example, the presence of central holes in the dust disk), but photometry alone cannot reveal the detailed morphology of the debris disks surrounding the stars. For example, without direct spatial information on the distribution of the material, it is difficult to distinguish between a disk and a shell of material. In particular, large planetary bodies can create asymmetries in the disk structures that would go unnoticed with photometry alone.

Spitzer has been able to image the thermal emission from dust in debris disks around the closest stars such as Fomalhaut (see Figure 16) and Vega. Hubble Space Telescope coronagraphic imaging has imaged debris disks in scattered light from small dust particles (Figure 17). The thermal and scattering properties of the disks allow us to place constraints on the amount and size of the dust grains in the disks. But, perhaps more importantly, the presence of asymmetries within the disks may indicate the presence of large planetary bodies orbiting the host stars. For example, in the Spitzer images of Fomalhaut, the disk is asymmetric at both 24 and 70 μm , and in the HST image, the disk is found to be off-center from the position of the star. An unseen planet may have given rise to these asymmetries.

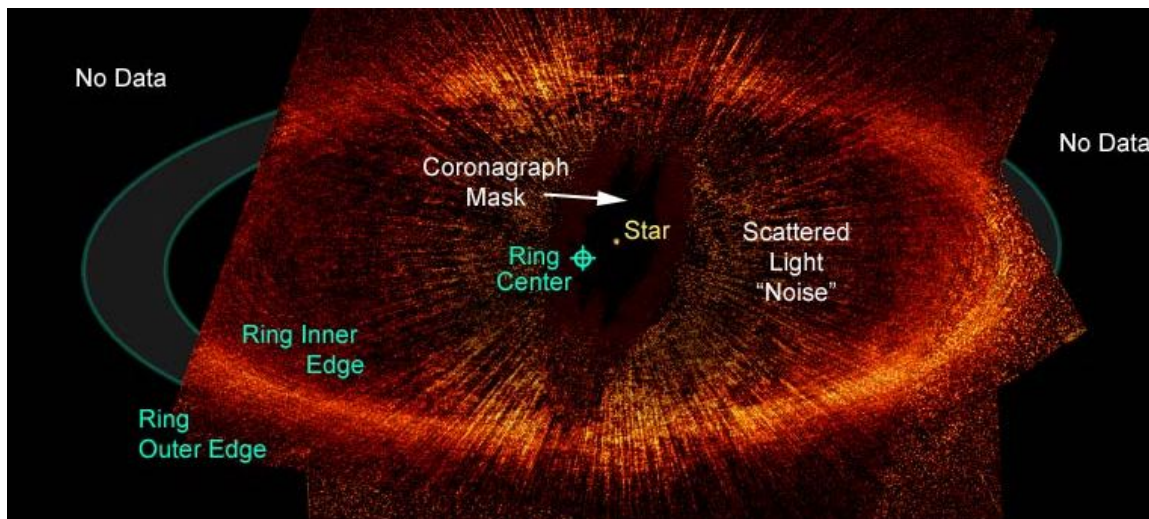


Figure 17. Visible light image of the circumstellar dust ring around Fomalhaut, taken with the High Resolution Camera coronagraph on the Hubble Space Telescope’s Advanced Camera for Surveys. This image shows that the center of the ring is displaced 15 AU from the location of the central star. The most plausible explanation for the displacement is that an unseen planet, moving in an elliptical orbit, is reshaping the ring with its gravitational pull. (Kalas, Graham, and Clampin, 2005.)

The HST detection of the disk around Fomalhaut, shown in Fig. 17, has demonstrated that it is possible to image a disk with an optical depth 15 times less than that of bright debris disk β Pictoris. It is not expected that many more such systems can be imaged at this level from HST or from the ground. However, if a 1.5–2-m class space-based adaptive optics coronagraphic mission were implemented, as may be possible within the scope of a NASA Discovery mission, then imaging of disks would be possible down to about 10 times our Solar System level in the Kuiper Belt region for hundreds of stars. Images of disks and their internal structures would be a key science return from such a mission.

While Spitzer will make excellent measurements of Kuiper Belt analogs in other planetary systems, it will detect only the most extreme exozodiacal disks. The next round of information on dust in the inner regions of disks will come from the various ground-based nulling interferometers planned to come into operation over the next few years, including the Keck Interferometer, the LBTI, and the VLTI/GENIE. Starting with Keck observations in 2007, the first surveys of exozodiacal clouds in the habitable zones of nearby stars will have a sensitivity of about 10 times the level of our Solar System. With their long baselines, the Keck Interferometer and the VLTI will detect emission between 0.1–1.0 AU for a star 10 pc away. Figure 18 illustrates the response of the Keck Interferometer. The LBTI, with its shorter 14-m baseline, will detect emission at larger distances from the star, in the range of 0.5–5 AU. In their first years of operation, these facilities will observe critical samples of stars to assess the strength of exozodiacal emission in and around the habitable zone. This will help determine whether many or all stars have more than 10 times the level of zodiacal dust in our Solar System, which would likely be a complication for efforts to image terrestrial planets in the habitable zones of nearby stars.

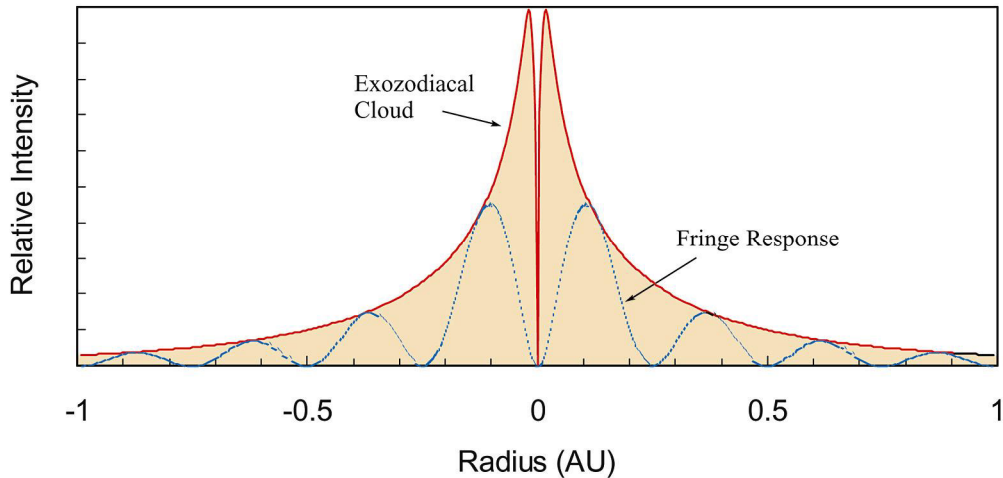


Figure 18. Cross-sectional view through an edge-on exozodiacal cloud at a distance of 10 pc, showing the emergent flux (solid curve), and the flux transmitted by the 10- μ m fringe pattern of the Keck Interferometer in the nulling mode (dotted curve). (E. Serabyn, JPL)

Observations made with ground-based nulling interferometers will resemble the TPF-I data in that resolved disk observations in thermal emission are quite sensitive to the intrinsic luminosity of the star; brighter stars generally have thermal emission that is more extended. Consequently, disk surveys by the Keck Interferometer, LBTI, and VLTI will likely emphasize A and F stars, rather than G and K stars. We may not be able to observe the exozodiacal dust environments of these later spectral type stars unless we undertake an analogous coronagraphic precursor survey.

Spectroscopy of Dust and Gas

Information on the nature (e.g., size and composition) of the dust grains in debris disks is vitally important to our understanding of planetary system formation and evolution. In particular, the composition of the dust grains is likely directly related to the composition of any unseen planetary bodies. For example, Spitzer spectroscopic observations of HD 69830 reveal a spectrum rich in silicate dust strikingly similar to dust grains found in comets in our own Solar System (Figure 19). The observed dust may be the result of asteroids colliding in a massive belt, producing copious amounts of small grains in the habitable zone around HD 69830.

Interestingly, HD 69830 shows no infrared excess at longer wavelengths (70 μ m), indicating that the presence or extent of a debris disk around potential TPF targets cannot be determined unambiguously from single wavelength observations. A Spitzer survey for silicate emission began in 2005, covering a sample of 80 potential TPF targets.

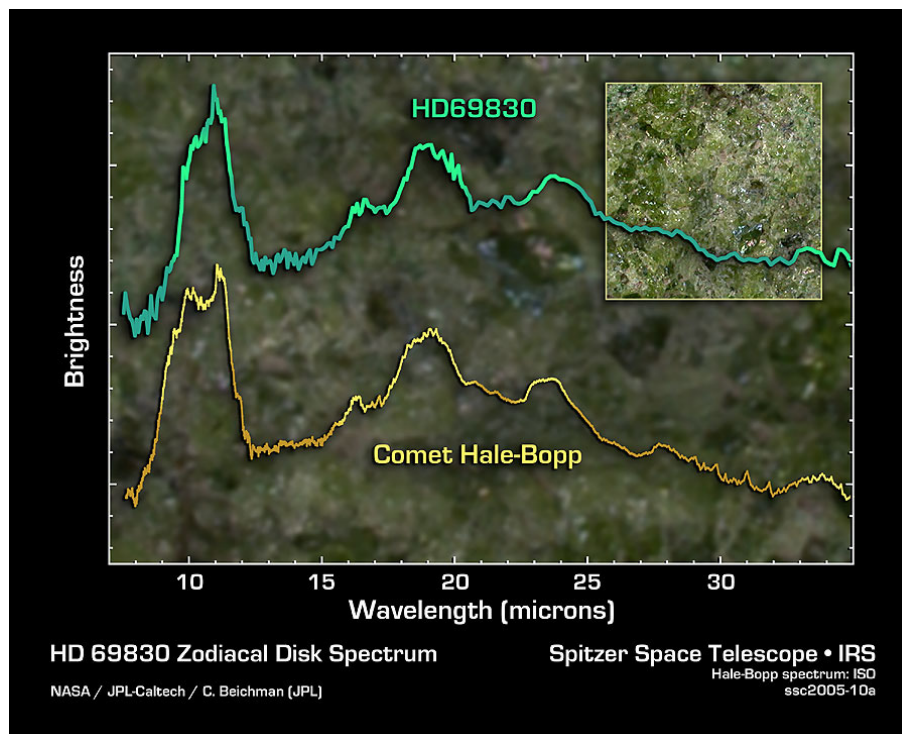


Figure 19. Spitzer Infrared Spectrograph (IRS) observations of the nearby star HD 69830 reveals dust grains of composition very similar to dust grains found in our own Solar System. The top spectrum is of HD 69830, and the bottom spectrum is of Comet Hale-Bopp. (Beichman *et al.* 2005)

In addition to dust grains, a few debris disks have been shown to contain a small amount of gas as well. This gas appears to be primarily atomic and ionic, as opposed to the mostly molecular gas in primordial and transitional disks. Spectroscopy of circumstellar gasses may provide information on the composition of the disk and its constituent bodies that is less readily available from dust observations. In addition, the gas abundance in debris disks is important for modeling of dust structures that have been attributed to the gravitational influence of unseen young planets (e.g., cleared zones, dust rings, and clumps).

Detections of gas in debris disks have been achieved with optical and ultraviolet spectroscopy. Except for one case, observation of resonantly scattered gas emission from β Pic at optical wavelengths (Olofsson *et al.* 2001; Brandeker *et al.* 2004), these detections have always involved absorption spectroscopy of edge-on disks. Such observations are sensitive to very small amounts of cold gas. Unfortunately, the geometric constraint that the line of sight to the central star must pass through the disk severely limits the number of disks that may be probed for gas in this way. In the longer-term, an ideal instrument to detect gas in debris disks and also to image new disks uncovered by Spitzer will be the Atacama Large Millimeter Array (ALMA), which is expected to begin operation late in this decade. With 64 antennas of 12-m aperture spread across baselines extending to 10 km, ALMA will achieve a spatial resolution of 30 mas (0.5 AU at β Pictoris; 4 AU in nearby star-forming regions). ALMA will provide detailed maps of the density, kinematic structure, and chemical structure of protoplanetary disks in molecular and atomic line emission, and of the dust continuum emission of nearby debris disks. With no stellar contrast problem at these wavelengths, ALMA should map more disks in greater detail than any prior astronomical facility.

Contributions to Navigator Science

It is important that the complete list of potential TPF target stars be well characterized. A crucial aspect of this work will be to determine the presence or absence of dust disks around these stars. Although selected stars may be studied through individual peer-reviewed proposals, a program coordinated between NASA and ESA is needed to make the best use of missions whose lifetime is limited. It will be important to ensure that the *complete* sample of potential TPF targets (~250 stars) is observed by missions such as Spitzer and Herschel.

The combination of high-resolution imaging of debris disks (Spitzer, Herschel, HST, JWST, Keck, LBT, and VLT Interferometers) with theoretical investigations of the dynamics of such systems (see Section 4.3) might lead to indirect detection of planets by gravitational perturbation of dust morphology.

Our estimate of the frequency of Earth-like planets may be improved through observations of the structure and evolution of dust and gas within debris disks in various star-forming environments. This would yield information including the total mass, the surface density, the temperature, the composition, and the distribution of gaps in these disks, leading to a greater understanding of the mass transfer rate, the compositional changes, and the persistence time scales of material found there.

Other than results from the Keck Interferometer, most observations of dust prior to TPF-C and TPF-I will measure the dust emission originating predominantly from regions more distant from the star than the habitable zone. Improvements to dust transport theory are needed to estimate the amount of dust in the habitable zone from observations of dust at larger distances. This may prove to be important in evaluating the mission concepts for TPF.

The greatest source of confusion in the background of a target star may not be background stars or galaxies, but structure in the star's exozodiacal dust disk. This region will be inaccessible to any telescopes other than TPF-C or TPF-I.

4.3 Theory and Modeling

Theoretical work on exozodiacal dust centers on two areas: understanding the origin and evolution of planetesimals in debris disks including the transportation and migration of dust and planetary bodies, and understanding and decoding the morphological appearance of debris disks.

Current State of the Art

Origin and Evolution of Planetesimal Belts

Theoretical models are needed to understand the dominant processes that regulate the evolution of debris disks around stars of various ages. Physical effects that need to be considered include the interaction between dust particles and gas with stellar radiation, and particles' growth and fragmentation associated with collisions. Models are needed to describe the origin and distribution of the residual planetesimals that may exist in debris disks. In the outer Solar System, the orbital distribution of Kuiper Belt Objects

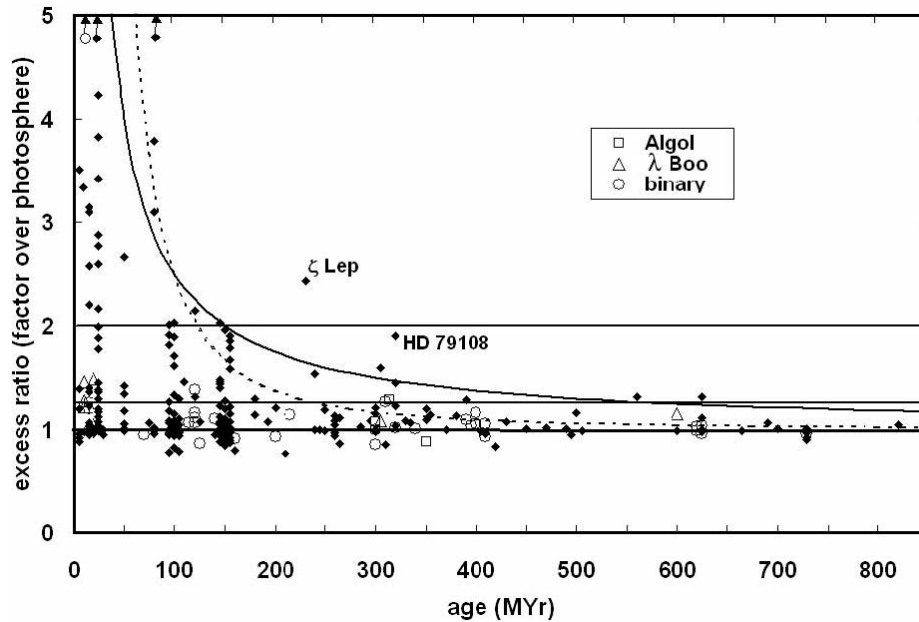


Figure 20. Strength of the 24- μm infrared excess plotted as a function of stellar age, demonstrating the general decline in dust mass but with large scatter out to 750 Myr. Excess emission is indicated as the ratio of the measured flux density to that expected from the stellar photosphere alone. The solid curve is an inverse time dependence; the dashed curve has an inverse time-squared dependence. (Reike *et al.* 2005)

suggests that a large fraction of planetesimals are scattered outward as a consequence of gravitational perturbation by giant planets. These models will have implications on the potential extent of planetary systems and the planet formation efficiency and rate near the habitable zone. The dynamical evolution of comets, and therefore of volatile and organic material, also needs to be examined for planetary systems with a range of dynamical filling factors and in a variety of stellar environments. The delivery of volatile and organic material by impacts of planetesimals may determine the evolutionary paths of life on habitable planets.

Theoretical analysis is also needed to assess the survival and replenishment of dust in debris disks. Figure 20 displays the amount of infrared excess above the stellar photospheres produced by small dust grains plotted as a function of stellar age. The plot shows a general decrease in the infrared excess as the stars age, indicating the removal of the dust from system or a decreasing dust production rate. The large scatter apparent at any age suggests that the production of dust is stochastic, dominated by a few recent large collisions. For example, the Solar System underwent a strong heavy bombardment period 700 Myr after formation (Gomes *et al.* 2005). This likely produced a spike in zodiacal dust production, greatly in excess of what is observed today or predicted by Figure 20. Further, HD 69830 (Figure 19), with a relatively advanced age of 2 Gyr, has exozodiacal emission 1000 times larger than the Sun, and significantly larger than what is expected from the data in Figure 20.

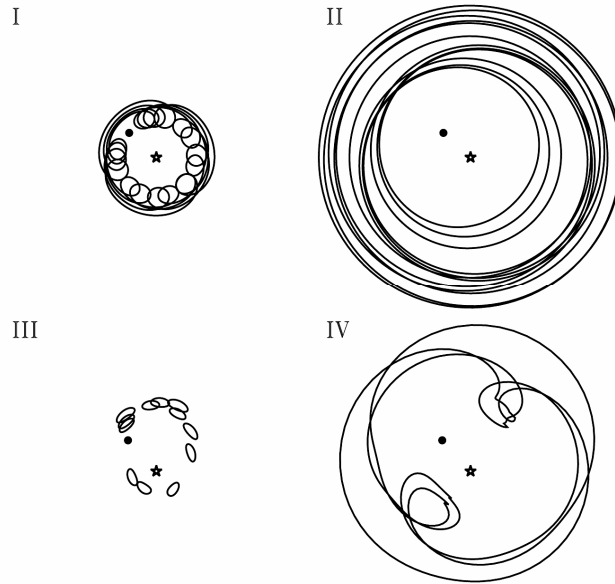


Figure 21. Approximate analytic description of the range of resonant structures a single planet can create in a collisionless cloud. Case I, a ring with a corotating gap at the location of the planet is exemplified by Earth's interaction with the solar zodiacal cloud. The other cases have been suggested as models for other debris disks, but not yet verified. (Kuchner and Holman 2003)

Decoding the Appearance of a Debris Disk

Debris disks often show dust structures (such as rings, clumps, and warps) that are generally attributed to the gravitational influence of unseen young giant planets (e.g., Heap *et al.* 2000; Holland *et al.* 2003). Analogous structures in our Solar System are the very narrow rings within Saturn's ring system confined by shepherding satellites and the clumps of zodiacal dust leading and trailing Earth in its orbit. Such structures are interesting for two reasons. They may provide another way to detect planets that is effective for stars not suitable for radial velocity or transit observations (young, active, and high-mass stars). In addition, unresolved clumps in an exozodiacal dust disk might possibly be mistaken for a terrestrial planet, at least initially.

Some debris disks contain sharp edges with apparent gaps, while others such as that around β Pictoris have warps, or inclined sub-disks. It is likely that many of these asymmetries indicate the presence of planets or other processes at work. For example, Figure 21 illustrates in a simple way the expected range of resonant structures a single planet can create in a collisionless dust cloud. There is much more numerical and analytical work to be done to provide a sound framework to understand the possible range of long-lived structures that may persist in an exozodiacal cloud.

The effect of gas in debris disks may be an important factor. Takeuchi and Artymowicz (2001) showed that a relatively modest amount of gas will strongly affect the dynamics of small dust grains, which are the grains most easily seen in optical and near- to mid-infrared disk images, and can lead to the formation of azimuthally symmetric structures like cleared zones or dust rings. This general conclusion is supported by

more recent modeling (Klahr and Lin 2006), which also showed that such gas-formed structures can persist after the gas is completely gone.

It will also be crucial to observe exoplanetary systems with known planets and disks to calibrate and test our models of planet-disk interactions. At present, the only example of a system where a known planet creates an observed structure in a debris disk is the solar zodiacal cloud. We need to either improve our understanding of the structures in our own zodiacal cloud or attempt to observe asymmetries in additional exoplanetary systems with debris disks.

Terrestrial Planet Formation and Delivery of Volatiles

In order for terrestrial-sized planets to acquire large quantities of volatiles such as water, giant planets are likely required to gravitationally stir up planetesimals and inject them into the inner disk. The gas composition in a debris disk may provide information on the composition of the planetesimals producing the disk. For example, recent far-ultraviolet spectroscopy of the gas in the well-studied β Pic debris disk has shown that carbon is extremely overabundant relative to every other measured element (e.g., $C/O = 18 \times$ solar; Roberge *et al.* 2006), despite the fact that the central star appears to have solar metallicity (Holweger *et al.* 1997). This overabundance likely reflects the composition of the parent material of the gas, which would have to be much more carbon-rich than expected based on what we know about Solar System asteroids and comets. Either the β Pic planetesimals producing the gas are selectively losing their volatile carbon compounds, or they are simply more carbon-rich overall than any Solar System planetesimal. The latter possibility has important consequences for any terrestrial planets that might be forming around β Pic and their volatile composition.

Expected Near-Term Progress

The next few years will see a wealth of new observational data on exozodiacal clouds. Most immediately are the observations from Spitzer, which will include measure of lower levels of exozodiacal emission than has previously been possible (<100 times the level of our own Kuiper Belt) around hundreds of stars with a wide variety of ages (millions of years to billions of years). Additionally, Spitzer will obtain information on the composition and size of exozodiacal material through spectroscopy of hundreds of disks.

A few years later, ground-based interferometers (Keck, LBTI, and VLTI) and large far-IR telescopes (SOFIA and Herschel) will map exozodiacal emission in the habitable inner reaches of other planetary systems. By the end of the decade, ALMA will begin high-spatial-resolution millimeter mapping of the dust and gas within debris disks. A robust theory program will take in all this information to better constrain our understanding of the formation and evolution of solid material in planetary systems, particularly the formation of rocky bodies like Earth. This synthesis of theory and observation will also advance our understanding of the environment of the early Earth when life originated using material from the final epoch of impact and in-fall.

Contributions to Navigator Science

A program of theory and modeling of exozodiacal dust is essential to knit together the disparate observational datasets described above into a coherent whole that we can use to extrapolate the detailed knowledge needed for TPF. To what extent is the presence of an exozodiacal disk a signpost of the presence of large rocky bodies (asteroids, comets, moons, Earths)? How do planets produce structures in

the exozodiacal cloud that could be a source of confusion in the search for planets? What processes produce the large-scale structure of the exozodiacal cloud, and how does that structure affect the detectability of planets?

4.4 Summary: Opportunities, Risk, and Priorities

Imaging of dust disks is a rapidly growing field. HST coronagraphy will continue to resolve high optical-depth reflected-light disks. Spitzer will study a large sample of stars for disks on scales of the Kuiper belt. Spitzer began its surveys for Kuiper Belt disks and bright inner zodiacal clouds in late 2003. The Keck Interferometer has begun nulling observations, and measurements of exozodiacal clouds (a few times our Solar System level) should be available in 2006, to be joined thereafter by LBTI and VLTI. Searches for disks around target stars are of inherent scientific interest and will likely occur naturally through the peer-reviewed proposal process on all these facilities.

It is now highly likely that we will be able to survey many hundreds of potential Navigator target stars with Spitzer. Since these observations are of high scientific interest, it is probable that these data will be obtained with little need for intervention into the normal time allocation processes.

It will nonetheless be important to ensure that the *complete* sample of potential TPF targets (~250 stars) is observed by missions of limited lifetime (e.g., Spitzer and Herschel). Thus, the TPF and Darwin Projects should work with NASA and ESA to ensure that a coordinated observing program to observe target stars is carried out. Most of the obvious targets are already scheduled for observations by Guaranteed Time or legacy observers. But any additional stars suggested as particularly important by the TPF-SWG should be observed during the open time on Spitzer. This information should be augmented by higher angular resolution observations with ground-based interferometers (operating in a two-telescope nulling mode) and observations with the Herschel Space Observatory. This information should be adequate to assess the importance of exozodiacal emission for the design of TPF-C and TPF-I.

Potential areas of risk include the failure of one of the interferometers to perform at the required level of sensitivity for observations of dust in the habitable zone. This risk is mitigated by the fact that there are three ongoing interferometer programs: KI and LBTI in the Northern Hemisphere, and VLTI/GENIE in the Southern Hemisphere. In addition, Herschel will add important observations at intermediate angular resolution between now and 2008. A coronagraphic precursor mission would be a valuable addition to the preparatory science program, allowing us to measure scattered light from exozodiacal dust clouds in a matter analogous to TPF-C.

4.5 References

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5 Target Stars

5.1 Objectives of Precursor Science

Relevance to the Navigator Program

What are the characteristics of stars, such as the Sun (shown in Fig. 22), as well as stars of other spectral types, that make them suitable hosts of habitable worlds? Of the stars that are suitable hosts, which ones are the easiest targets to observe in the search for planets? The answer to these questions will help develop preliminary target lists that will guide the execution of SIM PlanetQuest, TPF-C, and TPF-I. In the near-term the target lists will influence the mission concept reviews through the assessment of the exozodiacal light levels around nearby stars (as described in the previous chapter). In the long-term the factors to consider are those that will enhance the probability that TPF will discover signs of habitability and life.

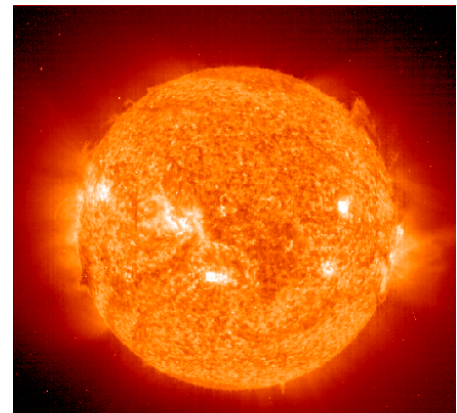


Figure 22. 304 angstrom image of the Sun, from the SOHO Extreme Ultraviolet Imaging Telescope. (NASA)

Metrics for Decision Making

The SIM PlanetQuest and TPF target lists will be developed using criteria that define the bounds of stellar properties necessary to support habitability. Many of these properties, associated criteria, and mission-specific details are described later in this chapter.

Schedule and Deliverables

In Pre-Phase A of TPF-C and TPF-I, preliminary, though well-developed target lists are necessary to assist the architecture design teams in their preparation for the mission concept reviews. With preliminary lists, the feasibility of an architecture design can be realistically assessed to provide support for entry into the mission's Phase A.

During Phase A of TPF-C and TPF-I, more detailed lists are necessary to allow an initial design of each mission and to set the scope of each observatory: the list of candidate stars will need to be estimated so that the angular resolution and sensitivity can be calculated. This will allow instrument parameters to be determined that will provide support for entry into Phase B.

Properties of Stars That May Harbor Earth-Like Planets

The astrophysical properties of interest in assessing the habitability of terrestrial planets include:

- Stellar Age
- Evolutionary Phase
- Spectral Type/Mass
- Variability
- Metallicity
- Galactic Kinematics
- Multiplicity
- Giant-Planet Companions

Each astrophysical property of a star has an influence on the existence and longevity of a circumstellar habitable zone. The target star lists for SIM PlanetQuest, TPF-C, and TPF-I will be developed to identify those nearby stars that are most likely to harbor Earth-like planets. As illustrated in Fig. 23, this will be done beginning with a list of all nearby stars and reducing the list using suitable criteria including variability, spectral type, luminosity class and multiplicity. The selection shown in Fig. 23 is one example of how a TPF target list might be derived. The ongoing effort to devise the absolute best SIM PlanetQuest and TPF target lists will involve setting appropriate limits of habitability based on diverse stellar properties, as well as the technical merits and limitations of the instruments being used to make the observations. Most of the selection criteria will be the subject of intense debate leading up to the launch of these missions.

Stellar Age: Despite our desire to understand the origin and evolution of life on other planets, terrestrial planets in very young planetary systems (especially those less than ~1 billion years old) may experience frequent life-suppressing impacts, and the atmospheres of such planets may not have well developed spectral biosignatures (e.g., oxygen, ozone, and methane). The biosignatures from these planets are therefore less likely to be detectable by TPF-C or TPF-I. On Earth, although abundant biogenic methane may have been present in our atmosphere prior to 2 billion years ago, the rapid rise of oxygen due to photosynthetic organisms did not occur until about 2.3 billion years ago (Kasting 2001). Exozodiacal dust emissions will also be greater for younger systems (Mamajek *et al.* 2004 and references therein), especially those at high orbital inclinations, which may make the properties of terrestrial planets less discernable with TPF-C or TPF-I. Starspots are also more abundant in the photospheres of young stars and can degrade the astrometric accuracy for SIM PlanetQuest. Therefore, it will be essential to have accurate age estimates for all potential target stars prior to the missions.

Evolutionary Phase: Evolutionary phase determines the width of the continuously-habitable zone, which shrinks as stars increase in brightness during their main sequence (hydrogen-burning) lifetimes, and disappears altogether when stars rapidly transition into helium-burning red giants (Kasting *et al.* 1993). The red giant phase itself lasts only about one-tenth as long as the main sequence lifetime, leaving little time for a new genesis of life on more distant terrestrial planets or moons. For these reasons, we would probably want to restrict our target selection to those stars on the main sequence for both TPF and SIM PlanetQuest.

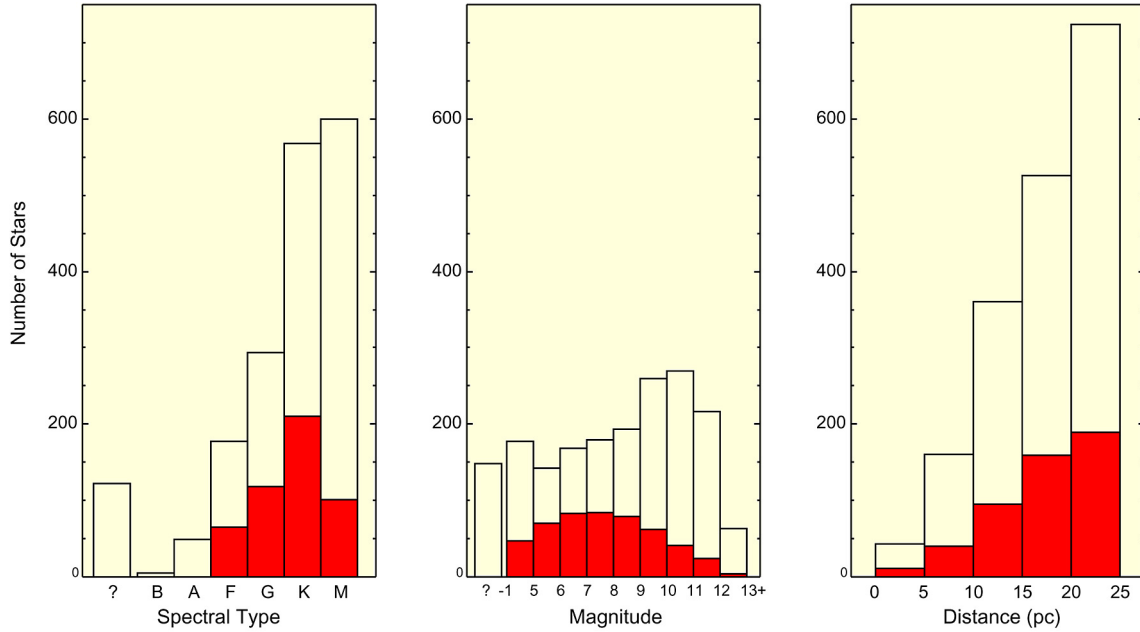


Figure 23. Distribution of potential TPF-I target stars as a function of spectral type, magnitude, and distance. All stars within 25 pc of the Earth (outlined areas above) were initially selected from the Hipparcos catalog, by choosing only those with a parallax of 40 mas or greater. Stars of spectral type F, G, K, or M were kept, and within those groups stars were rejected if they had composite or variable spectra. Only luminosity class V stars were then retained. All stars with specific variability types were removed. Stars were then also rejected if they had Hipparcos double or multiple flags or Hipparcos Annex flags of G, O, V, or X. Stars were also removed if they had a companion (or likely companion) within 10 arcseconds. The remaining 494 stars are shown by spectral type, magnitude, and distance, in the red shaded areas above. (Urban *et al.* U.S. Naval Observatory)

Spectral type and Mass: Stellar mass and spectral type are related to both age and evolutionary phase, in that all stars more massive than about twice the mass of the Sun leave the main sequence at an age younger than about one billion years. Thus, the one-billion-year continuously habitable zone vanishes for all main sequence stars earlier than about F0. It will, therefore, be essential to derive accurate spectral types for all potential SIM PlanetQuest and TPF target stars. Such a project is presently under way and will provide robust spectral MK spectral types for ~3000 nearby main-sequence stars (Gray *et al.* 2006).

Stellar Variability: Stellar variability, either stochastic (i.e., flaring) or periodic (i.e., sunspots), may cause climate changes or UV and X-ray emissions that are harmful to life. During the 11-year solar sunspot cycle, the Sun changes in brightness by 0.1 percent, with about this same level of stochastic variability during solar-maximum due to flaring (Lean 1997, and references therein). This activity level appears to be harmless. However, the Medieval Warm Period of the 1100s and Maunder Minimum in the 1600s resulted from longer timescale solar variations as large as 0.5%, a level of variability which, though not deleterious, does begin to noticeably impact both climate and biology (Soon and Yaskell 2003; Kelly and Wigley 1992). Stars exhibiting flaring or periodic variability in excess of about 1% may, therefore, not be habitable. M-type stars are of special concern here, given their close-in habitable zones and their tendency for luminous flares at high-energy wavelengths. Older M stars are not as variable as their younger counterparts and would still be observationally viable candidates for SIM.

Metallicity & Galactic Kinematics: Stellar metallicity is a reflection of the heavy element content of the parent cloud from which the star formed, and therefore indicates the likelihood that terrestrial planets (with their very high iron and silicates content) formed as well. So far, radial velocity searches for planets have verified the correlation between stellar metallicity and the presence of gas-giant planets. Metallicity and kinematics are also related, in that older stars tend to have both lower metallicity and higher velocity dispersion. For stars with $[\text{Fe}/\text{H}] < -0.4$ (about 40% solar abundance), the U, V, and W Galactic velocity dispersions increase by a factor of two (Edvardsson *et al.* 1993). Thus, stars that are not kinematical members of the thin disk of the Galaxy are less desirable targets for SIM PlanetQuest and TPF, unless spectroscopic data are available indicating a metallicity greater than about half the metallicity of our Sun. Highly elliptical orbits through the Galaxy may be of further concern in that these stars will pass through spiral arms more frequently, where high-energy radiation, cosmic rays, and even interstellar dust densities may affect planet climate and habitability (Doyle and McKay 1991; Clark *et al.* 1977).

Multiplicity & Giant-Planet Companions: The presence of stellar and giant-planet companions can interfere with the dynamical stability of terrestrial planets in the habitable zone (Holman and Weigert 1999; Turnbull and Tarter 2003). If possible, all potential SIM PlanetQuest and TPF targets should be surveyed for radial velocity variability with sensitivities capable of detecting Jovian-mass planets in the habitable zone. It may also be the case that giant outer planets in circular orbits contribute to the long-term stability of the habitable zone by dynamically shielding it from cometary bombardments. Very wide binaries do not pose a special concern — indeed, some known giant planets orbit within wide binary systems (e.g., 16 Cygni B, 55 Cancri A). Observationally, companions will certainly pose a problem if the additional shot noise from the second star interferes with TPF observations. Companions will be an additional source of noise if the companion lies within the SIM PlanetQuest three arcsecond aperture stop.

5.2 Observational Programs

Observations of Stars

Indicators of stellar youth all arise from the fact that stars are born with relatively high rotational velocities, and slow down in a predictable way via magnetic braking. This rotation, combined with convection zones in late F- through M-type stars, drives chromospheric activity and X-ray emissions, which also decrease with time as rotation slows (Welsh *et al.* 2006; Silvestri *et al.* 2005; Henry *et al.* 1995). Projected rotational velocities (which indicate a minimum for the true rotational velocity) greater than 10 km/s, and X-ray emissions in the ROSAT PSPC 0.1–2.4 keV energy range greater than 2.1×10^{28} erg/s, are both consistent with ages less than 1 billion years for G-type stars (Turnbull and Tarter 2003). The R'_{HK} calcium II H- and K-line chromospheric activity indicator tends to vary over time as a given star goes through activity cycles (like the 11-year solar cycle), but $\log R'_{\text{HK}} > -4.75$ indicates a chromospherically active star that is not more than about 2 billion years old (Henry *et al.* 1996). With accurate photometry and metallicity data, isochrone-fitting can be used to determine the age of main sequence stars, but this method is also uncertain by ~ 1 billion years, with uncertainties increasing for later-type stars (Lachaume *et al.* 1999; Ibukiyama and Arimoto 2002).

Variability is not just important to the planet finding missions as a youth indicator. Highly variable stars will cause a photocenter shift in the SIM PlanetQuest measurements, resulting in a reduction of the astrometric accuracy achievable for these sources. The Hipparcos mission was able to detect flux variations in the Hp bandpass of $\sim 3\%$ (a level at least five times greater than that of the Sun's flaring and 11-year cycle variability), and several variability flags are included in the Hipparcos catalog. Spectroscopic analysis, such as that carried out by Houk (e.g., Houk and Cowley 1975, and subsequent Houk spectral catalogs) for stars in the HD catalog, indicating emission lines ("e" flags, e.g., "M5Ve") or variable lines ("var" flags) are also useful in noting variable stars. There are a number of ongoing ground-based projects devoted to determining the variability for young SIM targets, and additional programs will be important for doing the same for the main sequence SIM and TPF targets.

Stellar metallicity can be estimated either through spectroscopic measurements (e.g., Cayrel de Strobel *et al.* 2001) or Stromgren photometry (e.g., Olsen 1983, and subsequent Olsen UBVY photometry publications). The two methods agree with one another quite well to within a few tenths of a dex in $[\text{Fe}/\text{H}]$ for metallicities greater than about $[\text{Fe}/\text{H}] = -1.5$ (Turnbull and Tarter 2003). The radial velocity planet-finding surveys are presently determining metallicities for all of their target star samples (e.g., Valenti and Fischer 2005). These and other groups are expanding their metallicity analysis to include other elements such as C in addition to Fe in order to derive a more robust metallicity estimate. It is interesting to note that Spitzer observations of debris disks have not found any correlation with the presence of a debris disk and the metallicity of the host star (Brydon *et al.* 2006). The possible correlation between metallicity and the presence of planets is no doubt more complex than currently understood; metallicity may be more strongly coupled to the migration rate of giant planets during formation in the protoplanetary disk (Sozzetti 2004).

Searches for Brown Dwarf and Giant Planet Companions

All potential target stars should be searched for low-luminosity stellar or sub-stellar companions through radial velocity measurements and high-contrast imaging. For known stellar binaries, the angular separation of the two components should be at least $10''$ for TPF to prevent the signal from a terrestrial planet from being overwhelmed by shot noise from the secondary star. The linear separation of the two components is also of concern for the dynamical stability of the habitable zone, and while the critical separation is dependent upon the eccentricity of the binary orbit and the mass ratio of the two components, these parameters are not usually known for longer period visual binaries. A fairly safe rule of thumb is that the observed linear separation should not be less than about ten times the size of the habitable zone (Holman and Weigert 1999).

It may well be that the most favored target systems will be those with exterior giant planets (indicating the presence of a planetary system), but without the dynamically disruptive giant planets near 1 AU. The complete system of stellar, sub-stellar, and Jovian planetary companions associated with each target star should be characterized to enable an assessment of the dynamical environment of the terrestrial planets that SIM PlanetQuest, TPF-C, or TPF-I might find, and to define the formative history of each individual planetary system. The discoveries of wide stellar companions to the planet-bearing stars υ And, HD 114762, τ Boo, 16 Cyg B, and the wide brown dwarf companions to the solar analogs HR 7672 and ϵ Indi (the latter just 3 pc away) demonstrate how vastly incomplete our knowledge is of companions to the likely target stars. Depending on the details of the initial mass function for binary stars, a large population of cool, low-mass brown dwarf companions could be present and have remained undetected by studies to date.

Beyond 5 AU orbital distances, the population of brown dwarf and giant planet companions has yet to be characterized. Direct imaging is the only way to make an inventory of the outer planet region of the target stars on TPF's programmatic timescale.

A program of very-high-contrast imaging should be initiated for all nearby stars that are likely target stars, with the near-term goal of detecting all companions earlier than spectral type T, and the medium-term goal of detecting all companions with mass greater than or equal to that of Jupiter. A database of non-detection upper limits from previous imaging work should be assembled and maintained to guide future survey work. Observational progress in the companion searches will come from additional HST/ Near Infrared Camera and Multi-Object Spectrometer (NICMOS) work, from existing Adaptive Optics (AO) and future extreme AO systems on ground-based telescopes, from Spitzer and JWST, and from future 2-m class space coronagraph missions. A by-product of the companion search will be an initial indication of any "bright" sky background objects that might confuse TPF's work at still fainter sensitivity levels.

There is a serious need for observational preparatory science within the target selection effort for SIM and TPF. Nearly all of the stars within 30 pc have missing information for the habitability indicators listed above. A concerted effort should be made to photometrically and spectroscopically monitor all main sequence A- through M-type stars within 30 pc, for the sake of determining metallicities, ages, kinematics, variability, and the presence or absence of companions and identifying the most favorable target stars.

High-Contrast Imaging of Environments of Nearby Stars

Related to the search for low-mass stellar companions would be high-contrast imaging of the background around nearby stars. SIM, TPF-C, and TPF-I must detect light from planets in the presence of confusing signals. Dust disks have already been mentioned as an important research area for TPF preparatory science. Imaging of the background of targets is also important, as is modeling of the instrument response to fields with emission other than that from the planet. In some cases, the results may influence the final choice of target stars.

Conventional HST and ground-based coronagraphic imagery have demonstrated that high-contrast images of nearby stars do not have the featureless background that would make detection of nearby faint nebosity or planets easy. The brightness of an Earth at 10 pc is $V = 30$ mag. While a visible-light measurement of this depth is possible with many orbits of HST observation, it is probably not achievable relatively close to very bright target stars. Experience has shown that fields with a high galactic latitude typically contain only one to a few point sources, but may have numerous faint galaxies in the field. Space Telescope Imaging Spectrograph (STIS) fields ($52'' \times 52''$) near ϵ Eri were observed to levels of $V \sim 29$ mag. These fields were found to contain two galaxy clusters. Not all stars of interest for planet searches will be at high galactic latitude; observations of other stars (e.g., HD 163296) near the galactic plane have backgrounds that are dominated by stars but which may still contain one to a few galaxies. While there are ongoing efforts to collect high-contrast images of SIM/TPF targets in crowded, low-galactic latitude regions, the closest targets will be out of the field-of-view at the epoch of observation, requiring deep, wide-field observations for potential targets.

Those targets with structured backgrounds will affect both TPF-C and TPF-I. Extended nebosity (of whatever source) hampers PSF subtraction and spectral deconvolution techniques and may necessitate

observations at more spacecraft orientations in order to obtain a clean measure of the PSF (with consequent demands upon instrument stability). TPF-I, especially operating at 10 μm , will be subject to confusion with background dusty galaxies.

The brightness of an Earth at 10 pc in the infrared is 0.3 μJy at 10 μm . Unfortunately, the sensitivity and angular resolution of Spitzer are poorly suited for measuring the background fields for TPF. While Spitzer can reach a noise level of 1 μJy at 8 μm in a few hours of observing, it will not be able to achieve that level at an angular separation less than an Airy ring (2.5" for Spitzer at 8 μm) away from sources that are one million times brighter! Observations with a ground-based AO system at 2 μm may be the most relevant way to characterize TPF fields in the infrared, but it should be recognized that these will fall far short of the desired sensitivity or angular resolution. Even with a relatively poor temporal baseline (a few years instead of a decade) it will be important to use the 3-, 5-, and 10- μm coronagraphic capabilities on JWST to characterize TPF targets.

5.3 Theory and Modeling

Contamination of the Surface Layers of Host Stars

The accretion of residual planetesimals and the consumption of some terrestrial planets contaminate the surface layers of their host stars with metal-rich material. Theoretical analysis of the effects of enhanced opacity in the outer layers, the mixing of the newly added material, and the associated effects on stellar oscillations are important for the inference of terrestrial planet formation in metal-enriched stars with known gaseous giant planetary companions. This effect may prove to be very small except for stars that are sufficiently more massive than the Sun such that they do not have a large outer convection zone.

Spectral Energy Distributions of Host Stars

The physical and chemical properties of the atmospheres of exoplanets depend on both the details of their formation and the radiative forcing from the host star. The presence and detectability of planetary atmospheric features will depend on the coupling of atmospheric photochemistry, much of which is driven by the UV flux of the star and the atmospheric thermal structure, which is an outcome of the spectral energy distribution of the host star throughout the visible and infrared. Modeling of the coupled planetary processes of atmospheric chemistry and thermal structure, therefore, requires knowledge of the spectrum of the host star, including any significant absorption or emission features, over the entire wavelength range from the UV to the far-IR. In particular, the stellar UV radiation can strongly influence the detectability of ozone, and this effect needs to be understood over a range of possible conditions. The relationship between stellar spectral type, which is based on information gathered in the visible, and the potential range of UV characteristics for stars in that spectral type should also be explored. Differences in UV flux for a given spectral type may have significant impacts on both the likelihood of planetary habitability, and therefore the star's suitability as a target star, as well as the relative detectability of biosignatures such as ozone.

Dynamics of Planetary Systems

Many of the planetary systems targeted by SIM PlanetQuest and TPF will be those with a known Jupiter-mass planet at large separations, or even hot Jupiter systems for which the habitable zone lies outside the orbit of the close-in planet. Prior to the missions, all stars with known planetary systems should be modeled to determine the stability of terrestrial planets within the habitable zone (e.g., Jones *et al.* 2005; Turnbull and Tarter 2003; Marcy *et al.* 2002; Jones *et al.* 2001). In many of these systems, the possibility of terrestrial planets in the habitable zone can be ruled out. For other known giant-planet-bearing systems where the habitable zones are not influenced by either the presence of giant planets or major resonances between giant planets, the possibility of habitable planets is still contingent upon the absence of any further-out (undiscovered) giant planets that could give rise to resonances that destabilize the habitable zone. For potential TPF targets known to host a giant planet at a few AU, a continued radial velocity search for additional giant planets out to at least 10 AU is important in determining habitable zone stability, even if the habitable zone is presently deemed “safe.”

5.4 Target Stars and Mission Studies

In preparation for these planet-finding missions, all of the projects have begun developing their optimized target lists based on both the observational properties of the target stars and technical specifications of the instruments that will observe those stars. All target lists are optimized as much as possible to maximize the potential science yield of each mission. While the science goals of each mission are similar, the methods being used to find and characterize the planets and the limited amount of available observing time result in target lists that are somewhat distinct but with some overlap. Indeed, each mission will rely on the one preceding it to provide supplemental information allowing the latter mission to further optimize its observing scenario. All the missions use the Hipparcos catalog as the basis for their target lists.

SIM PlanetQuest Target Stars

SIM PlanetQuest presently has three key projects devoted to planet finding: The Extrasolar Planet Interferometric Survey (EPICs; Shao, PI), Discovery of Planetary Systems (Marcy, PI) and the Search for Young Planetary Systems and the Evolution of Young Stars (Beichman, PI). The first two are devoted to looking for Earth-mass planets around nearby stars, while the third one will detect Jupiter-mass planets around young stars in nearby associations and star-forming regions. The EPICs SIM key project is divided into a Discovery of Planetary Systems Tier-1 and Tier-2 observing strategy. The Tier-1 sample consists of 250 stars to be observed using narrow-angle observations that reach a 1- μ s single measurement accuracy through the additional observations of a set of reference stars within 1.5 degrees of the target star. The Tier-2 sample consists of 2000 stars observed with wide-angle measurements achieving a 4- μ s end-of-mission accuracy that relies completely on the surrounding astrometric grid stars being observed for the entire SIM project over the whole sky.

A SIM-optimized target list has been derived from an initial list of 2350 stars taken from the Hipparcos catalog with distances less than 30 pc (Turnbull 2004). All stars with $V > 7$ are removed since this is the limiting magnitude for the integration time assumed in the narrow-angle observing scenario. Stars with stellar companions within one arcsecond of the primary star were removed, to avoid contamination of the

primary star's fringe. All stars were removed that had stellar companions orbiting with semi-major axes within a factor of ten of the radius of the mid-habitable zone of the primary star. This is a conservative limit at which a companion will not have a significant gravitational effect on a planet within the habitable zone (Holman and Wiegert 1999). Possible giant stars were also screened out by the following process: stars catalogued as luminosity class III were removed if they had luminosity consistent with a giant star, but kept if their luminosity was consistent with a dwarf; stars catalogued as dwarfs were removed if they had luminosity exceeding that expected for a dwarf star. After these cuts, 575 stars remained. The list was further optimized by ranking the stars in descending order of the stellar astrometric signature that would be induced by an Earth-mass planet at mid-habitable zone. The final list consists of 545 stars and is ranked in order of those planets with the largest astrometric signature. The list is also optimized for narrow-angle astrometric observing by applying a weight to those stars with the greatest number of potential reference stars and with reference stars that are symmetrically distributed around the star.

TPF-C Target Stars

For TPF-C a high premium is placed on its technical performance for many reasons: the mission may have a lifetime of only five years; exposure times for planets are typically days in length; any single search has a low probability of finding a planet; stars are viewable only a fraction of the year; and planets move and hide in the field of view. In this pressured, information-starved environment, the people operating TPF-C must make excellent decisions about what star to observe next. That decision involves technical questions and issues such as: What stars offer the greatest likelihood of a discovery at the least cost of time? Can we be sure if a faint feature in a searching image is a planet and not a background object? If we find a planet, what must we do to ensure it is not lost?

The metrics of TPF-C's technical performance with a given star involve combinations of instrumental parameters, extrinsic stellar characteristics, and minor but interesting roles for two intrinsic stellar properties, mass and luminosity. See Fig. 24 for an example of how two such parameters, brightness and separation, are related to the detection probability of an Earth-like planet around nearby target stars. The metrics include the productivity or discovery rate—search completeness (or expected number of planets found assuming all stars have one) per exposure time—and abilities to disambiguate planets (distinguish one from another) and predict future viewability. The key instrumental parameters are aperture (which governs the collecting area, central field obscuration, and astrometric accuracy), throughput, (to which the exposure time is inversely proportional); and solar-avoidance angle of the sunshade, (which determines how many days of the year a star is observable). The important extrinsic stellar characteristics include brightness (which governs exposure times), closeness (which governs the hidden fraction of planetary orbits), and angular magnitude of planetary motions. Also included are sky location and proper motion, which govern the apparent motion of a star against the background. Luminosity governs the relationship between equilibrium temperature and star-planet distance and means that planets of a given temperature are better resolved but fainter around higher-luminosity stars, and vice versa. Stellar mass is important for its uncertainties, which contribute to the uncertainty of orbit estimations, particularly for the purpose of predicting planetary recovery.

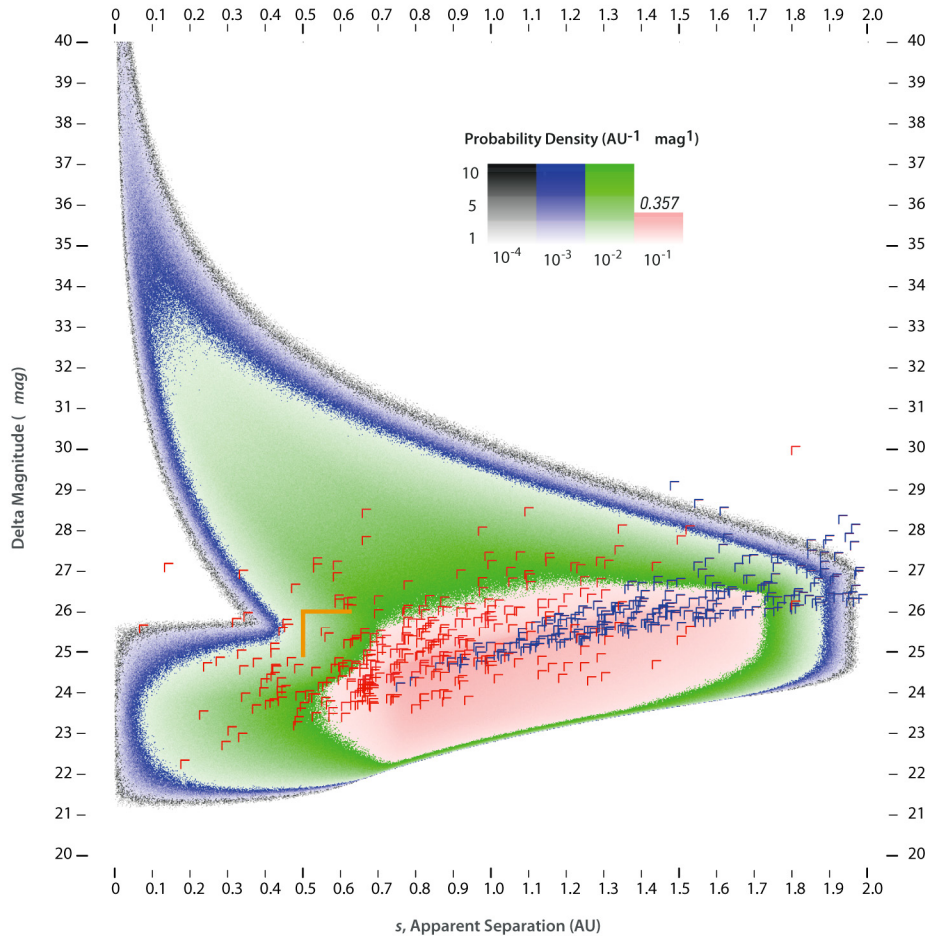


Figure 24. Distribution of probability density vs. angular separation s and Δmag for terrestrial planets in the habitable zone for the case of a planet with geometric albedo of 0.2, semi-major axis 0.75–1.8 AU, and eccentricity 0–0.1. The plot is based on 100 million random planets and shown for $L = 1$. The corners mark the integration zones for computing the completeness on individual valid stars (equivalent positions for $L = 1$). Red: the 198 stars with highest priority in an optimized first search using a total of one year of exposure time. Blue: the 247 lower-priority but still valid stars. Orange corner is the fiducial case for Earth at 8.82 pc. The completeness is the probability density integrated below and to the right of a corner. The high priority stars are shown at their optimized values of delta mag 0. (Brown 2006.)

The TPF-C target list^{**} draws stars from the Hipparcos catalog using qualification criteria related to main-sequence residency, main-sequence lifetime, distance, and adjacent fields with no known stars. Some 1408 stars satisfy these four qualification criteria: (1) on the main sequence, (2) closer than $d = 30$ pc, (3) no known companion within 10 arcsec, and (4) color $B-V > 0.3$, which is thought to imply a main-sequence lifetime longer than a billion years, long enough for life to develop under suitable conditions. The target list comprises the 136 of the 1408 qualified stars that are most productive for the baseline design and a habitable-zone distribution of planetary orbits.

^{**} A database of target star information particularly tailored to TPF-C may be found at http://sco.stsci.edu/tpf_tldb/ and http://sco.stsci.edu/tpf_top100/.

The summed completeness for the initial search of the whole target list is 32. This is the expected number of planets found assuming all stars have one ($\eta_{\oplus}=1$). The average individual completeness is 0.24, but the lowest 24 values are less than 10% of the highest value, which is 0.8 for Alpha Centauri B. However, it is not enough to only detect the planet once. We must confirm that it is orbiting the star (i.e., not a background source), and we would like to be able to continue to observe it into the future, to learn its orbit and search for spectral features relating to life.

The clear conclusions are that (1) target star selection for TPF-C must take technical performance fully into account, (2) the impacts of the selection effects and biases of technical performance on the TPF-C science program must be studied and reconciled with the science requirements, and (3) the correct scale of the TPF-C mission—the size that can reasonably satisfy the science requirements when the technical performance of stars is taken fully into account—is yet to be determined.

TPF-I/Darwin Target Stars

The TPF-I (NASA) and Darwin (ESA) missions will detect and characterize exoplanets at mid-infrared wavelengths through the use of nulling interferometry and formation-flying telescopes. Although some aspects of the missions currently differ, they have almost identical science and technology requirements and very similar target lists.

Catalogs of candidate stellar systems have been prepared for both TPF-I (Dubovitsky and Lay 2004) and Darwin (Eiroa *et al.* 2003; Kaltenegger 2004). In each case the initial list was created from the Hipparcos catalog, and a series of science and engineering criteria were applied to remove unsuitable targets. The

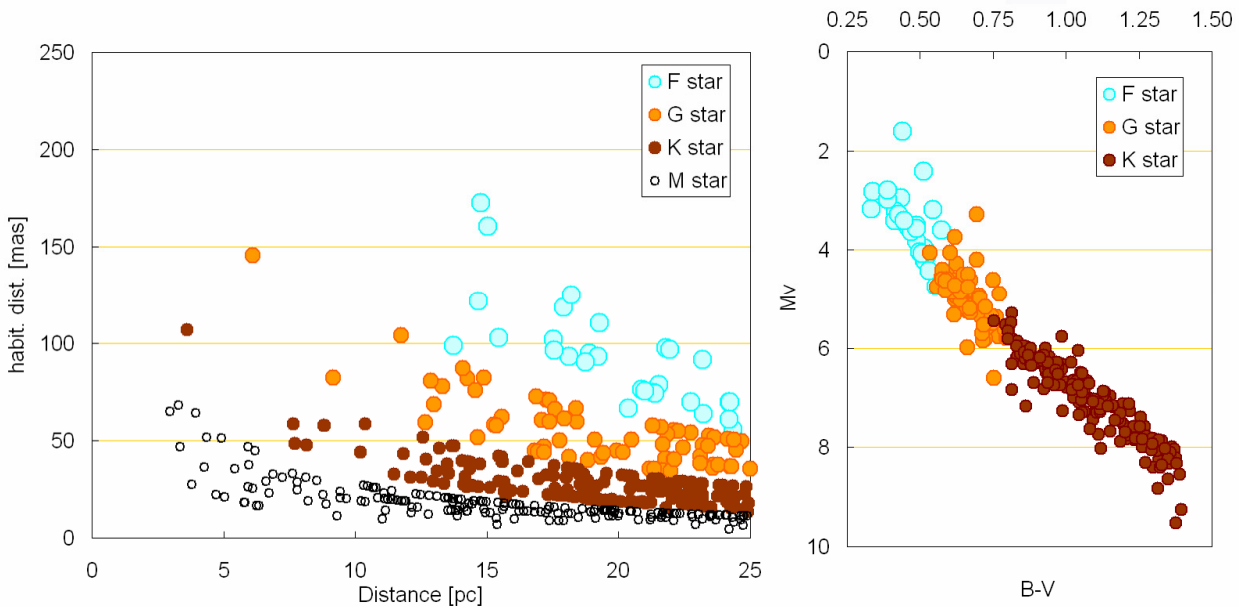


Figure 25. Angular distance of the Habitable Zone for the Darwin target stars (left), and color-magnitude diagram for same stars (right). It is obvious that most target stars are main sequence, while a few have already evolved off it. The different colors show the different spectral types. (Kaltenegger *et al.* 2006)

Table 5. Science and Engineering Criteria for Selection of TPF-I Candidate Targets

Parameter	Constraint	Remaining Stars
Science Culls		
Distance (Hipparcos catalog)	< 30 pc	2350
Apparent magnitude	< 9	1299
Bolometric luminosity	< 8	1284
Luminosity class	IV, V	1247
B-V index	> 0.3	1184
Variability	< 0.1	1143
Companions further than	50 AU	1014
Engineering Culls		
After science culls		1014
Field of regard	Ecliptic latitude < 45 deg	650
Multiplicity	Separation > 10"	620

Hipparcos catalog provides distance, spectral classification, multiplicity and stellar variability, which was then augmented with information from other sources, such as spectral type, metallicity, X-ray luminosity, rotation, and Strömgren photometry. The TPF-I science criteria are summarized in Table 5 together with the number of stars remaining after each successive criterion is applied. The initial list of 2350 stars is reduced to 1014. The two engineering criteria are also listed in Table 5. The ecliptic latitude limit is required to keep the spacecraft shaded from the Sun, and excludes approximately two-thirds of the remaining stars. The resulting TPF-I list has 620 candidates, compared to 446 for Darwin (the difference is mostly due to the 25-pc distance cut-off for Darwin, versus 30 pc for TPF-I).

Figure 25 shows observable properties of Darwin target stars. The lists are complete for F-type, G-type, and early K-type main sequence stars. Later M spectral types, which should be numerous, are not yet included. Data for essentially all M stars that could be included in the list should be provided by ESA's GAIA mission, scheduled for launch in 2012.

The TPF-I/Darwin missions observe in the mid-infrared and are sensitive to the thermal emission emanating from the planet (as opposed to reflected starlight). For a given distance therefore, the flux from an Earth-like planet at the center of the Habitable Zone is independent of the spectral type. At the same time, an M-dwarf star has a much lower luminosity than an F-star, so the contrast ratio is much more favorable for the M-dwarf case (less stellar rejection is required from the nulling system). On the other hand, the planet has a much smaller angular offset from the star, since the Habitable Zone is even closer to the star for the weak M-dwarf. From Fig. 25 we see that the angular offset of a planet at 15 pc in the center of the Habitable Zone will be ~150 mas, compared to ~15 mas for an M-dwarf. Much longer interferometric baselines are required in the latter case.

5.5 Summary: Opportunities, Risk, and Priorities

Recommendations

To make the most productive selection of target stars in the Navigator Program, it is crucial to better understand, through observation, synthesis, and theory, the stellar characteristics that favor both habitability and detectability of planets.

Several stellar characteristics are required as input to theoretical planetary models that can assess both habitability and detectability of planetary characteristics based on stellar type. In particular, accurately calibrated full-wavelength-coverage spectra (between different instruments) are needed, as extrasolar planetary atmosphere characteristics are sensitive to the spectral energy distribution from the UV to the far-IR. Several existing space observatories have the capabilities necessary to contribute to this effort, and existing data (such as International Ultraviolet Explorer [IUE] spectra) are available for a large fraction of TPF candidate stars. However, these data may require recalibration, or supplementation, with data from other observatories.

In addition to intrinsic stellar characteristics, it is important to characterize each target's circumstellar environment to assess detectability of planets. Imaging of target fields requires high angular resolution and high dynamic range so that faint background objects can be detected. Since many target stars will have large proper motions, imaging observations with HST done years before TPF-C is launched offer the prospect of identifying objects that may affect TPF, but which will be too close to the target to be separated on images taken at the epoch of TPF-C or TPF-I.

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6 Signs of Life

6.1 Objectives of Precursor Science

Relevance to the Navigator Program

TPF-C and TPF-I distinguish themselves from similar missions that seek to determine the number of habitable worlds in our Galaxy by striving for direct detection of terrestrial exoplanets. Directly detecting the light from terrestrial planets will allow their photometric, spectral, and temporal characterization. Since all exoplanets will appear as unresolved points of light, the detected spectra will include light integrated across the disk of the planet, such as that shown in Fig. 26.

TPF-C and TPF-I will measure the spectra of the atmospheres of habitable worlds. It is therefore important to create self-consistent theoretical models of planetary characteristics and evolution if we are to understand the plausible range of terrestrial planets that we may find. These models can help determine the instrumentation requirements and the search strategies for each TPF mission, and provide a theoretical framework for analysis of the mission data.



Figure 26. Simulated image of a cloud-free, illuminated Earth as seen from the Moon. (Woolf *et al.* 2002)

Metrics for Decision Making

A major goal of the TPF missions is to provide biologists and planetary scientists with spectroscopic data that will yield evidence of planetary habitability and life. At visible and infrared wavelengths, the habitability markers and biosignatures that have been identified include spectral features of molecular oxygen, water, carbon dioxide, ozone, and methane. What spectral bands should be observed and with what spectral resolution in order to provide convincing evidence of habitability and life? Recommendations must be made to establish the wavelength band limits for the optical coronagraph and mid-infrared interferometer designs. Recommendations must also be made for the required spectral

resolution in each band. Although Des Marais *et al.* (2002) made preliminary recommendations for wavelength ranges and spectral features, this work remains to be refined and extended, and it will likely be an ongoing subject of debate.

The success of the TPF missions will depend to a large extent on our ability to interpret the evidence for habitability and life that may be found in the spectra of planetary atmospheres and surfaces. Many factors will influence and complicate the appearance of likely habitability markers and biosignatures. It is important to the development of the science requirements for each mission that all the relevant factors be considered. A systematic approach to this problem should include the following lists:

1. A quantitative list of conditions necessary and sufficient for life as we know it should be developed. Here “life” includes any of the usual Earth-like forms: plants, animals, and microbes, i.e., carbon-based life dependent on liquid water. This list would include items such as temperature, liquid solvent presence, abundances of gases, trace elements, radiation ranges, solid surface, energy sources, and the presence of an atmosphere.
2. A quantitative list of signs of life (biosignatures) that are *necessary*, *sufficient*, as well as *probable*, should be developed. This list would include items such as thermodynamic disequilibrium, product gases, liquids, solids, reflection spectra, transmission spectra, and emission spectra.
3. A list of conditions that encourage life should be developed. This list would include items such as weather, climate variations, stress from such variations, rotation rate of planet, stellar ultraviolet and x-ray fluxes, and mass of atmosphere.
4. A list of “anti-biosignatures” should be developed. This list would include the identification of atmospheric constituents whose presence would greatly decrease the probability of habitability or the presence of widespread life.

Together these lists, and the considerations that go into generating them, will prove valuable in guiding TPF instrumentation, and the interpretation of TPF data.

Schedule and Deliverables

In Pre-Phase A, a preliminary version of the above four lists is needed prior to the mission concept review. These lists will provide strong guidelines for the wavelength range and spectroscopic resolution needed to detect life in each wavelength regime, and help to assess technological readiness.

In Phase A, these lists need to be developed in more detail to set the parameters of the instrumentation. In particular, this will allow filters and spectrometers to be developed that are suited to the characterization of habitable or Earth-like planets.

Signs of Habitability and Life

With arbitrarily high signal-to-noise and spatial and spectral resolution, it is relatively straightforward to remotely ascertain that Earth is a habitable planet, replete with oceans, a greenhouse atmosphere, global geochemical cycles, and life. Clues to Earth’s characteristics are found throughout its visible to mid-infrared spectrum. Strong spectral signatures from CO₂ and H₂O indicate habitability, including the presence of an atmosphere and liquid water, while signatures from the trace gases O₂, O₃, CH₄, and N₂O

provide compelling evidence for life. However, searching for the signs of habitability and life in the observations of other planets with limited signal-to-noise ratio and resolution and no spatial resolution will be far more challenging. This is due to the intrinsic faintness of exoplanets, the difficulty in separating a planet's radiation from that of its parent star (the Earth–Sun intensity ratio is about 10^{-7} in the thermal infrared and about 10^{-10} in the visible), and the possibility that the planets found will not resemble those already known in our Solar System. Understanding a wide range of planetary characteristics, and the resultant features observable in a disk-averaged spectrum, will help to determine the optimum wavelength regions for planetary detection, and allow us to determine the required spectral resolution, signal to noise, and observational strategies to unambiguously assess planetary habitability, and the possible presence of life.

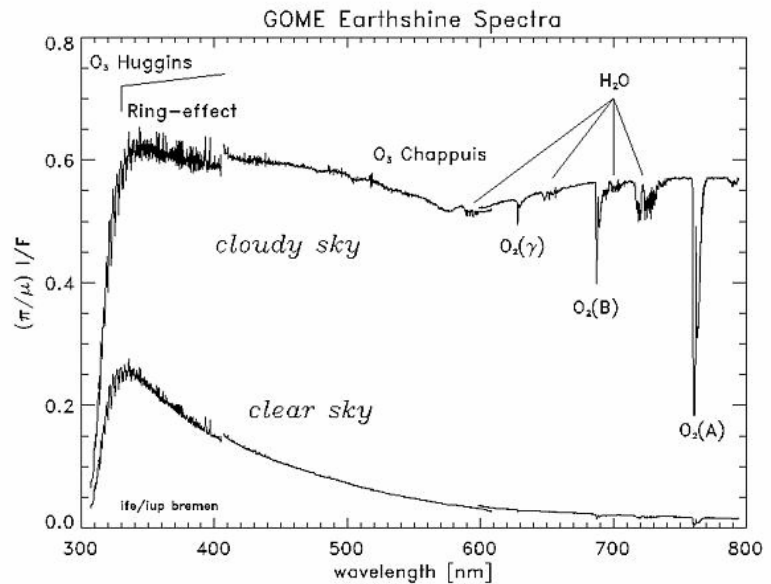


Figure 27. GOME UV-optical spectra of Earth showing habitability markers (H_2O) and biosignatures (O_2 , O_3). (Burrows *et al.* 1999)

To explore the plausible range of habitable planets, and to improve our understanding of the detectable ways in which life modifies a planet on a global scale, specific science objectives include:

- *Biosignatures.* Understand the variety of spectral and temporal (diurnally and seasonally varying) biosignatures, both surface and atmospheric, including signatures of ozone, oxygen, and methane. Other potential biosignatures from different metabolisms should also be explored and characterized. The relative robustness of life detection using a combination of planetary characteristics and biosignatures identified across a broad wavelength range should be explored. This research would be directly relevant to defining TPF instrument requirements such as wavelength range, spectral resolution, and signal- to-noise ratio.
- *Degeneracies.* Understand what planetary conditions can be uniquely inferred from low-resolution, full-disk spectra at visible, near-IR, and thermal wavelengths; and identify when a multiplicity of physical conditions can produce similar spectra. This research would also be directly relevant to defining TPF instrument requirements.
- *False positives.* Determine what abiotic planetary processes can give rise to planetary characteristics that mimic biosignatures, and determine what ancillary measurements, if any, would be required to separate false from true biosignatures.
- *Anti-signatures.* Identify combinations of gases thought to be antithetical to habitability or the existence of life. For example, large abundances of certain gases such as SO_2 , would likely preclude the presence of a surface ocean. Similarly, the presence of atmospheric gases that are

strongly favored by certain metabolisms may indicate that abundant life is not present to consume them. Such information would help in formulating TPF instrument requirements as well as evaluating the spectra of exoplanets.

- *Temporal Changes.* Understand surface and atmospheric changes for terrestrial planets, on a range of observational timescales, including periodic changes on daily (rotation), and seasonal (orbital) timescales, and chaotic changes such as cloud cover. Also explore the effect of long-term evolutionary changes (geological and biological history) on planetary global characteristics and disk-averaged spectra. This research will help us optimize observation sampling schemes on hourly to yearly timescales.
- *Planetary Evolution and Habitability.* Learn how terrestrial planet environments interact and evolve with their parent star and with the biosphere over a planet's lifetime, and learn how this affects planetary global characteristics, including habitability (and the resultant disk-averaged spectra) over time. This research will improve our understanding of the extent and evolution of the habitable zone over a star's lifetime, for planets of very different compositional types, and improve our ability to recognize habitable planets at different stages of biological and geological evolution.
- *Formation of Habitable Planets.* Improve our understanding of the origin of planetary systems, and the early history of volatile delivery and loss mechanisms for terrestrial planets of varying size and mass. This research would help us define the potential range of terrestrial planet compositions and the likelihood for habitable worlds.

For a general review of characterization of exoplanets and biosignatures, see the papers by Schneider (2003) and Des Marais *et al.* (2002).

6.2 Observational Programs

Earth is the only known planet capable of supporting life, so research motivated by the above objectives is necessarily based on observations, data interpretation, and predictive modeling of Earth. This section reviews recent progress in observations of Earth.

Current State of the Art

Thanks to Earth-observation satellites such as the Global Ozone Monitoring Experiment (GOME)^{§§} and the Scanning Imaging Absorption Spectrometer for Atmospheric Chartography/Chemistry (SCIAMACHY),^{***} there is an extensive collection of UV-optical spectra of Earth. Although individual spectra are localized, they are very useful in showing how the UV-optical spectrum changes with location, season of the year, and cloud cover and height. The reflectance of the cloud-covered region is much higher than that of the ocean surface. The spectrum of the clouds clearly shows absorption by H₂O, the A and B bands of oxygen and the Chappuis band of ozone, although the latter feature is difficult to retrieve because of its broad,

^{§§} <http://earth.esa.int/ers/gome/>

^{***} <http://envisat.esa.int/instruments/sciamachy/>

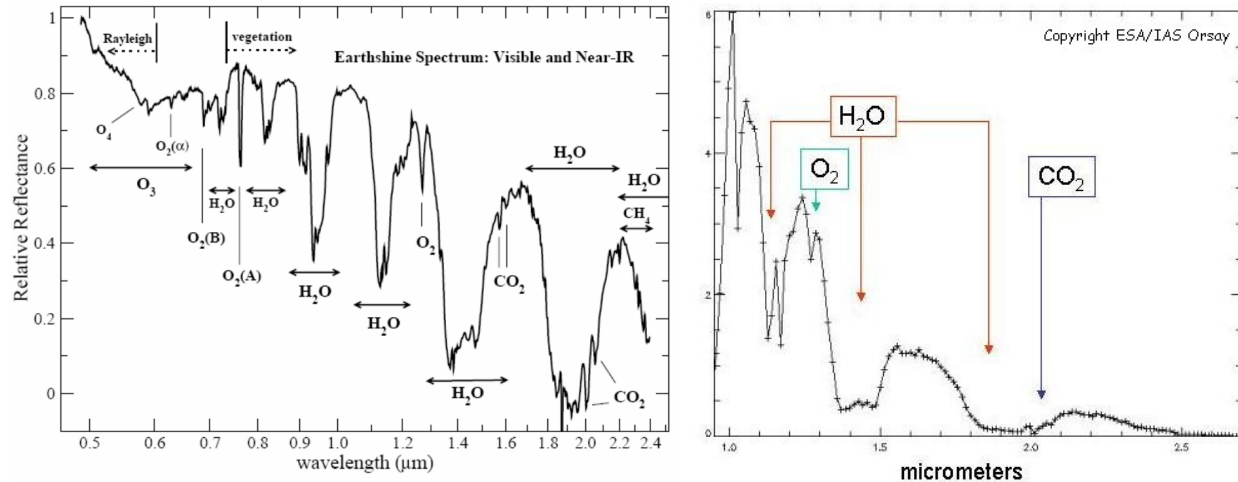


Figure 28. (left) Visible-near-IR spectrum of Earthshine, (right) near-IR Earth spectrum from Mars Express. (Turnbull *et al.* 2006; European Space Agency, Institut d’Astrophysique Spatiale)

shallow profile and confusion with Rayleigh scattering. Better ozone features are found in the near-UV as shown in Fig. 27. Sensitivity to both O_2 and O_3 is important in that the ratio of their strengths is an indicator of the evolutionary stage of photosynthetic activity if an independent pressure estimate exists (Selsis *et al.* 2002; Schneider 2003). The greater information offered by the near-IR and near-UV argue for broadening the spectral range of TPF-C.

Earth’s own spectrum, observed directly by Mars Express, or as “Earthshine” indirectly by reflection from the Moon (Fig. 28), shows strong evidence of the presence of an atmosphere (Rayleigh scattering), habitability (H_2O absorption features), and vegetation (O_2 when coupled with evidence for water).

The visible Earthshine spectrum has been studied by several groups (Arnold *et al.* 2002; Woolf *et al.* 2002; Turnbull *et al.* 2006). Earthshine sometimes shows a sharp (but weak) increase in flux longward of $0.7 \mu m$ (“vegetation red edge”). In the near-infrared ($>0.9 \mu m$), the spectrum of Earthshine shows much stronger absorption features of H_2O , several features of CO_2 at moderate strength, an additional moderately strong O_2 feature at $1.26 \mu m$, and several weak CH_4 features. Note the dependence of the strength of all those features on the cloud coverage (Hamdani *et al.* 2006).

The U.S. Geological Survey (Clark *et al.* 2003) has compiled an extensive spectral library of minerals, mixtures, volatiles, and various forms of vegetation covering the spectral range from 0.2 to $3.0 \mu m$. These data, along with spectra from the Johns Hopkins University and JPL, are included in the ASTER spectral library^{†††} covering both the optical and infrared regions of the spectrum. The library has become an essential resource for identifying features in the spectrum of Earth and other rocky planets in the Solar System and beyond, and it is helpful in showing how a given spectral signature may be due to multiple materials.

^{†††} <http://speclib.jpl.nasa.gov>

The spectrum of Earth's vegetation (e.g., grass, leaves) shows a remarkable jump in reflectance at $\sim 0.7 \mu\text{m}$, known as the vegetation red edge (VRE). Models of a cloud-free Earth-like planet indicate that the VRE can be relatively strong in cloud-free disk-averaged spectra. In the observed disk-averaged spectra of Earth, however, the strength of the edge is a few percent at most, because vegetated areas are sparse, and the feature is washed out by clouds, which are highly reflective. Consequently, many observations of Earthshine have resulted in only tentative detections. Monitors of the VRE in Earth's disk-averaged spectra show that its strength is correlated with the surface area of cloud-free vegetated regions. Detecting the VRE on another planet will pose additional challenges, as no *a priori* information on surface composition or cloud cover will be available. In addition, "light-harvesting organisms" on exoplanets may produce spectral signatures that differ from Earth's VRE, in strength, shape, and spectral position (Tinetti *et al.* 2006). False positives for the VRE may occur with surface abiotic materials such as cinnabar and sulfur that also have strong reflectance edges. For all these reasons, time variability appears to be the key to detecting and properly identifying weak surface biosignatures on Earth or exoplanets.

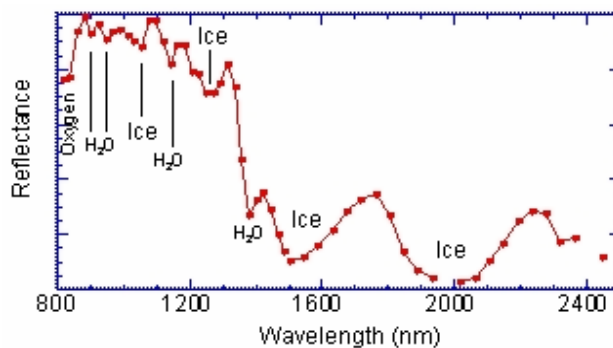


Figure 29. Spectrum of Antarctica obtained by the Near-Infrared Spectrometer on the NEAR mission. (JHU/APL)

Viewing geometry also influences the detected signal. As an example, if an exoplanet is detected in a face-on orbit, then we will be viewing the planet pole-on. A spectrum of Antarctica obtained by the Near-Infrared Spectrometer on the Near-Earth Asteroid Rendezvous (NEAR) probe (Fig. 29) shows what to expect if the planet — like Earth for 10% of its history — has polar ice caps. The current polar Earth spectrum shows strong absorption by water ice, but it also shows absorption by oxygen as well as water vapor, that could suggest an inhabited planet.

While on its way to Mars, the Mars Global Surveyor's Thermal Emission Spectrometer (TES) obtained a unique whole-disk, near-IR and thermal-infrared spectrum of Earth centered over the Pacific Ocean, as shown in the right panel of Fig. 30 (Christensen and Pearl 1997). A Geosynchronous Orbiting Environmental Satellite 9 (GOES-9) thermal-IR image of Earth taken at the time of the TES observation indicates that the observed region was dominated by water and clouds.

In order to interpret spectroscopic data in the context of possible biological activity, we need to know the planet's size and temperature. Estimates of planet size and albedo (crucial for determining the characteristics of a planet) can be determined in both wavelength ranges, directly from mid-IR observations, and through atmospheric modeling in the visible or near IR range due to the possible albedo range.

The mid-IR spectrum shows strong atmospheric absorption features of CO_2 , ozone, and water vapor. In the mid-IR, the classical signatures of biological activity are the combined detection of the $9.6\text{-}\mu\text{m}$ O_3 band, the $15\text{-}\mu\text{m}$ CO_2 band, and the $6.3\text{-}\mu\text{m}$ H_2O band or its rotational band that extends from $12 \mu\text{m}$ out into the microwave region (Selsis *et al.* 2002). (Were there no water, the flux distribution would follow the 270-K blackbody curve at the long- and short-wavelength ends.) The flux distribution and spectral features indicate an average temperature of 270 K for the ocean surface, polar regions, and cloud tops.

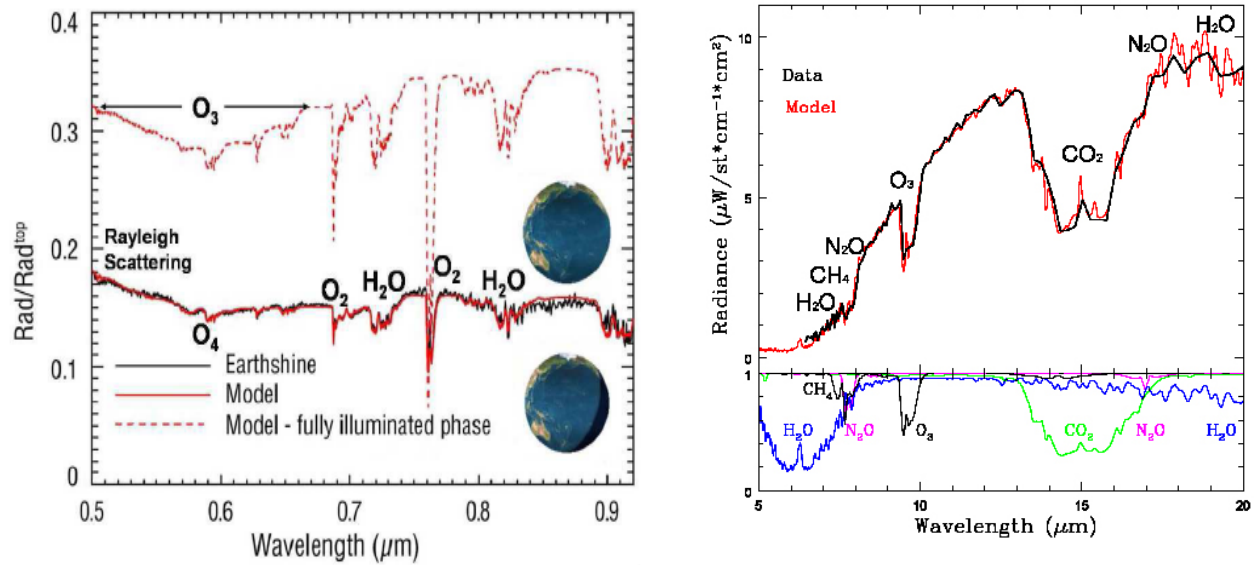


Figure 30. Model and disk-integrated spectrum (left) in the visible and in the infrared (right). Data from the left panel by Woolf *et al.* 2002, reproduced from Tinetti *et al.* 2006. Data from the right panel by Christenson *et al.* 1997, reproduced from Kaltenegger *et al.* 2006).

The 9.6- μm O_3 band is highly saturated and is thus a poor quantitative indicator, but it is an excellent qualitative indicator for the existence of even traces of O_2 . CH_4 is not readily identified using low-resolution spectroscopy for present-day Earth, but the methane feature at 7.66 μm in the IR is easily detectable for early Earth-type planets. There are no N_2O features in the visible and three weak N_2O features in the IR at 7.75 μm , 8.52 μm , and 16.89 μm .

Expected Near-Term Progress

Long-term observations of Earthshine will be used to discern diurnal, seasonal, and inter-annual variations, and UV-optical spectroscopic observations by Earth-viewing satellites are expected to continue.

Recommendations

1. Continued observations of Earthshine are needed to discern diurnal, seasonal, and inter-annual variations.
2. Development of an easily accessible, public database of satellite observations of Earth are needed to give insight into the variety of spectroscopic signatures of land, ocean, and clouds in different environmental conditions and to provide component spectra for creating disk-integrated spectra of Earth.

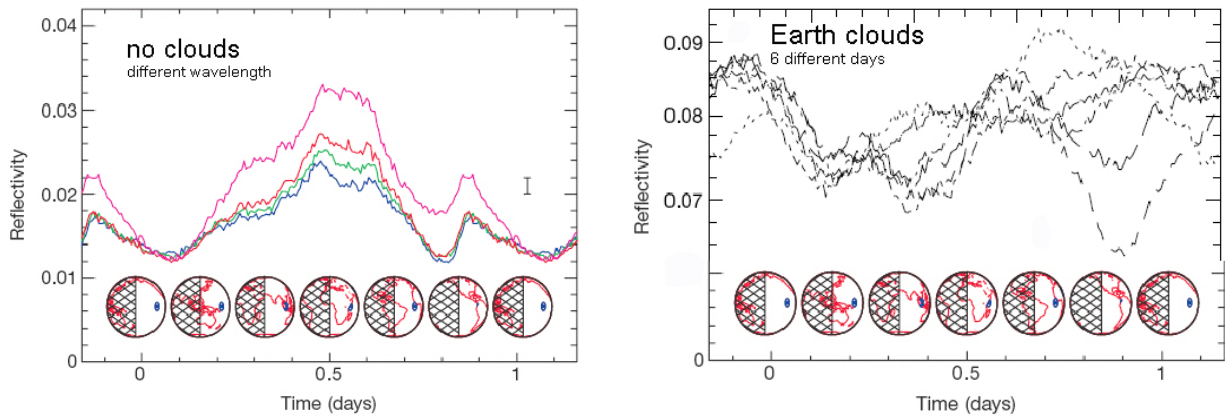


Figure 31. Rotational light curve for a cloud-free Earth model (left). The pink, red, green, and blue curves correspond to wavelengths of 750, 650, 550, and 450 nm, respectively, and their differences reflect the wavelength-dependent albedo of different surface components. Theoretical rotational curves using cloud-cover data from satellite measurements taken on six consecutive days, 13–18 April 1986. Model daily light curves are shown at 550 nm for our Earth model with clouds, as viewed from quadrature. The light curves are sampled at 4-minute intervals, and the Poisson noise is due to Monte Carlo statistics in our calculations. The images below the light curve show 1) the viewing geometry with the cross-hatched region un-illuminated, 2) a map of Earth in red outline, and 3) the region of specular reflection from the ocean, as a small blue oval. (Ford *et al.* 2001)

6.3 Theory and Modeling

Theoretical modeling permits the visualization of a range of different observational viewing geometries and timescales for studying extrasolar terrestrial planets, as well as allowing us to explore the plausible range of habitable planet environments and spectra. These studies ultimately improve our understanding of how to recognize a habitable planet, and of the detectable ways in which life modifies a planet on a global scale.

Daily and yearly variations of planetary flux: On a cloud-free Earth, the diurnal flux variation at visible wavelengths caused by different surface features rotating in and out of view could be high, assuming hemispheric inhomogeneity. When the planet is only partially illuminated, a more concentrated signal from surface features could be detected as they rotate in and out of view on a cloudless planet (see Fig. 31, left panel). Earth has an average of 60% cloud coverage (see Fig. 31, right panel). Note that clouds increase the reflected flux from a planet and thus improve the contrast ratio.

The yearly flux variation in the IR can distinguish planets with and without an atmosphere in the detection phase like that shown in Fig. 32. Note that the graph shown assumes a circular orbit (Selsis 2004; Gaidos *et al.* 2003).

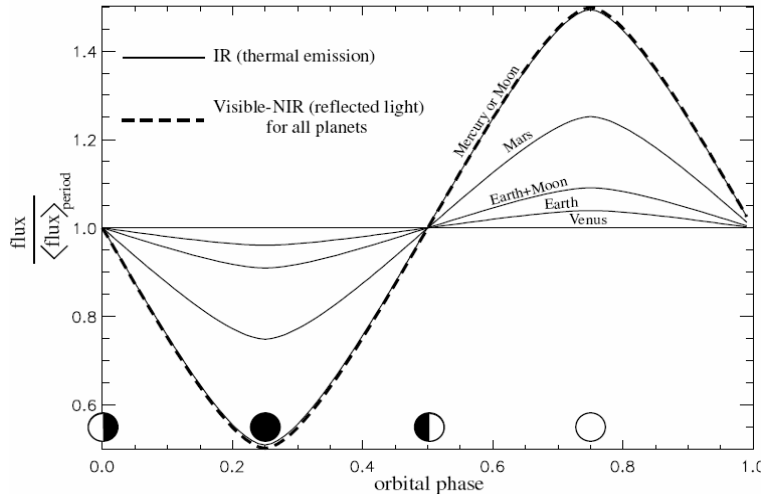


Figure 32. Yearly light curve for planets with and without an atmosphere in the thermal infrared. (Selsis 2004)

Planetary Characterization and Evolution Models

Since TPF-C and TPF-I will study the global atmospheric and surface properties of planets that they detect, the most relevant evolutionary models to study are those that have direct implications for a planet's atmosphere. In our own Solar System, and especially on Earth, the process of plate tectonics plays a key role, as it is the means by which the surface and mantle interact and cycle volatiles. This process can contribute significantly to planetary habitability by providing one link in the carbonate-silicate weathering cycle, which buffers atmospheric CO_2 . It is not fully understood and should be modeled in the future.

Unfortunately, some of the basic planetary data that we will obtain—such as radius, mass, and albedo—will not provide significant data regarding a planet's formation history, or its current state. Our own Solar System illustrates the difficulty. Venus and Earth, which are nearly identical in size, mass, density, and the abundance of at least some volatiles (N_2 , CO_2), currently have radically different surface environments. Since planetary evolution can be so divergent, it is important to understand the divergent evolutionary paths that terrestrial planets may take after their formation. Venus, Earth, and Mars provide three examples of “end states” of terrestrial planet evolution, but there are probably many more possible outcomes that should be explored and understood.

The Evolution of Atmospheres and Climates on Rocky Planets

Evolution of the planetary surface and atmosphere is determined by many factors, including the spectral energy distribution of the host star, the astrophysical environment, the planet's initial volatile inventory, and subsequent geologic activity and biology. Consequently, terrestrial planet evolution needs to be studied as a whole to establish bounds to habitability. Earth's atmosphere has experienced dramatic evolution over 4.5 billion years, and other planets may exhibit similar or greater evolution, and at different rates. Changes in any greenhouse effect and the efficiency of atmospheric circulation will drive climate change. These

changes could not only influence a planet's habitability but also limit the habitability of planets that have non-Earth-like rotation rates or obliquities, for example tidally locked planets around M stars.

Models of volatile evolution for Earth-like planets could be used to explore the implications of changes in the inventory and distribution of volatiles between the interior, surface, and atmospheres of rocky planets. Calculation of the dynamical transport of volatiles through planetary systems can be carried out for systems whose giant-planet configurations are already known. Water is of special interest here, both because of its obvious importance to habitability and because many nebular models predict its depletion at distances corresponding to the habitable zone.

The Evolution of Earth's Atmosphere

A useful topic for continued study is the evolution of Earth's own atmosphere. We know very well which gases (e.g., O_2 and O_3) represent easily detectable biomarkers in Earth's present atmosphere. However, we are also reasonably sure that, although O_2 and O_3 were virtually absent prior to about 2.3 billion years ago, life itself was present back to at least 3.4–3.5 billion years ago. Figure 33 shows model spectra of the change of detectable biomarkers in the spectrum of an Earth-like planet throughout its geological history.

So, there was at least a billion-year period during which one would have needed to look for other biomarker gases in order to determine from remote sensing that Earth was inhabited. Methane has been suggested as a possible biomarker gas for this period, as it is produced by anaerobic microbes and is also reasonably stable against photolysis. Today, methane is produced mostly biologically, but there may also be small abiotic sources as well, such as reactions of warm seawater with Fe- and Mg-rich rocks deep beneath the seafloor.

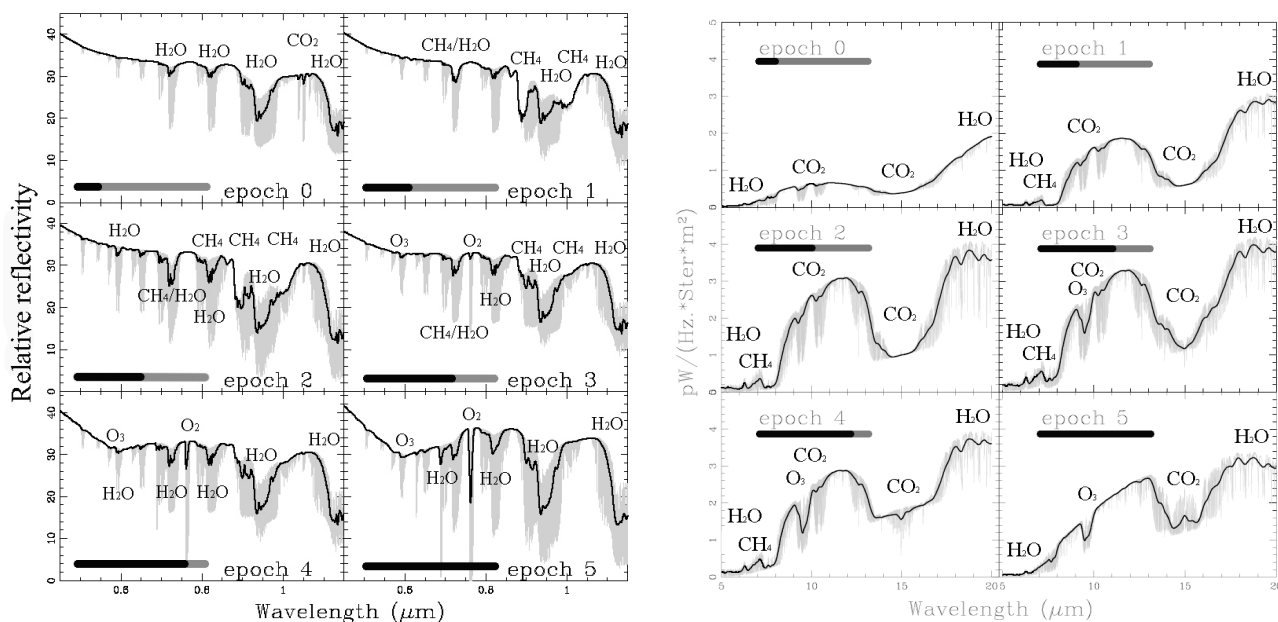


Figure 33. The visible/near-infrared spectral features (left) and mid-infrared spectral features (right) on an Earth-like planet change considerably over its evolution from a CO_2 -rich (epoch 0) to a CO_2/CH_4 -rich atmosphere (epoch 3) to a present-day atmosphere (epoch 5). The black lines show spectral resolution of 70 (left) and 25 (right) comparable to the proposed TPF-C and TPF-I mission concept designs. (Kaltenegger *et al.* 2006)

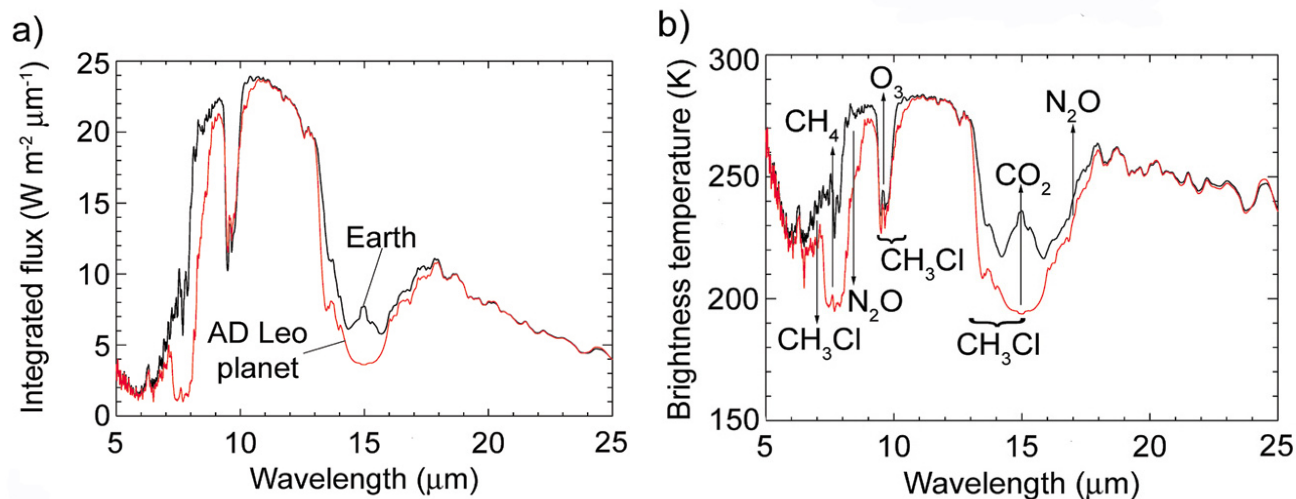


Figure 34. Simulated IR spectra for Earth-like planets around the Sun (black) and the M star AD Leo (red). The left-hand panel shows radiances, and the right-hand panel shows brightness temperatures. AD Leo has a brightness equal to 0.023 times that of the Sun and an effective radiating temperature of 3400 K. The Earth-like planets have $\text{N}_2\text{-O}_2$ atmospheres with 21% O_2 . The AD Leo planet has an orbital radius that gives it the same average surface temperature as Earth. The surface fluxes of biogenic gases are the same as those measured (or computed) on Earth. (Segura *et al.* 2005)

These reactions form serpentine minerals along with partially oxidized iron in the form of magnetite, Fe_3O_4 . As the iron is oxidized from Fe^{2+} to Fe^{3+} , dissolved CO_2 in the seawater is reduced to CH_4 , which then leaves the mid-ocean ridge system through off-axis hydrothermal vents. It is uncertain, however, whether this process is entirely abiotic, or whether abiotically generated H_2 is converted to CH_4 by methanogens living within the vent systems. We need to better understand modern abiotic methane sources in order to be able to estimate how much methane was produced abiotically in the past. Similarly, we need to develop models of anaerobic ecosystems to estimate what the biological methane flux may have been in the distant past. Without this type of information, it will be difficult to interpret what a positive identification of CH_4 might mean.

However, O_2 , O_3 , and CH_4 are good biomarker candidates that might be detected by a low-resolution TPF instrument. There are good biogeochemical and thermodynamic reasons for believing that these gases should be ubiquitous byproducts of carbon-based biochemistry, even if the details of alien biochemistry are significantly different than the biochemistry on Earth. Production of O_2 by photosynthesis allows terrestrial plants and photosynthetic bacteria (cyanobacteria) to use abundant H_2O as the electron donor to reduce CO_2 , instead of having to rely on scarce supplies of H_2 and H_2S . The advantages of this innovation would presumably apply to alien plants and bacteria as well. O_3 is produced photochemically from O_2 , so it carries much the same information about the prevalence of life. O_3 builds up nonlinearly with O_2 abundance, however, so it is a good indication of photosynthetic activity even at O_2 concentrations 100 times smaller than today. CH_4 is expected to be a ubiquitous by-product of metabolism in anaerobic environments because it is extremely stable thermodynamically. Models of early Earth atmospheres suggest that both CO_2 and H_2 should have been present at reasonable concentrations. Thus, organisms could have made a living from the reaction $\text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$. The thermodynamic energy yield of this reaction would be the same on exoplanets, provided that their atmospheres contained similar concentrations of CO_2

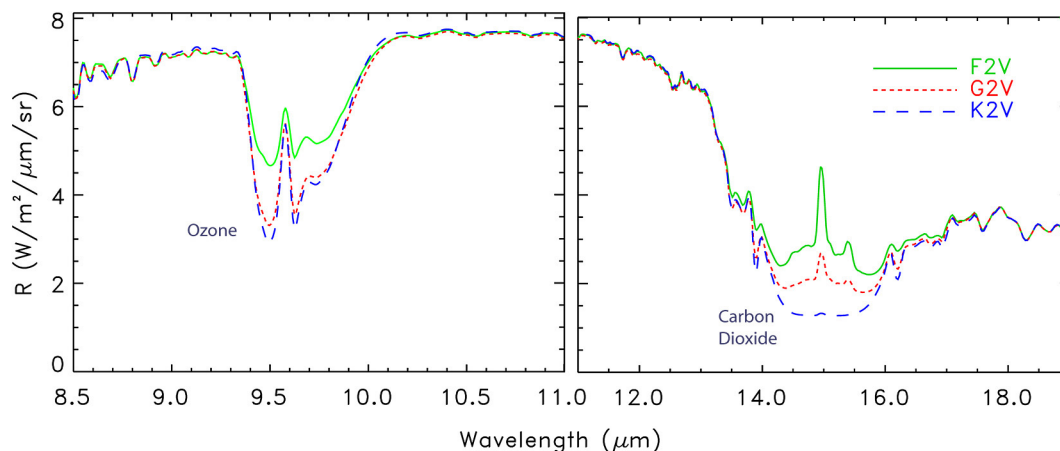


Figure 35. These spectra show the appearance of Earth-like planets orbiting within the habitable zones of stars of F2V, G2V, and K2V stellar type. In each case, a weakly-coupled radiative/photochemical atmospheric model was used to determine the equilibrium atmospheric composition and vertical structure for a planet with Earth’s modern atmospheric composition, and radiatively forced by the UV to the far-infrared spectrum of a star of each spectral type. A sophisticated radiative transfer model was then used to create a synthetic spectrum of the global spectral appearance of the planet from space, using the equilibrium atmospheric composition as input. (Segura *et al.* 2003)

and H_2 . Hence, there is every reason to believe that alien organisms, if they exist, would also have evolved the capability of generating methane.

However, we should also be cautious about focusing entirely on O_2 , O_3 , and CH_4 . Although these gases appear to be our “best bets” for detecting life remotely, they are individually somewhat ambiguous. Like CH_4 , O_2 also has abiotic sources that might be important on some types of Earth-like planets. These include a transient source from photolysis of CO_2 , followed by recombination of O atoms to form O_2 ($\text{O} + \text{O} + \text{M} \rightarrow \text{O}_2 + \text{M}$), as well as a net source from photolysis of H_2O , followed by escape of hydrogen to space. (The first source is transient because the CO formed from CO_2 photolysis will eventually recombine with oxygen to reform CO_2 .) We need to understand the abiotic sources of O_2 , so that we can identify when it might constitute a “false positive” for life. We should also explore the question of whether there might be other biogenic trace gases that might accumulate to detectable concentrations in other planetary atmospheres.

Some preliminary work on this subject has already been done. Nitrous oxide, N_2O , is a promising biomarker in some types of atmospheres. Nearly all of Earth’s N_2O is produced by the activities of anaerobic denitrifying bacteria. N_2O would be hard to detect in Earth’s atmosphere, as its abundance is low at the surface (0.3 parts per million by volume [ppmv]) and falls off rapidly in the stratosphere. On a low- O_2 early Earth, its abundance would be even smaller because it photolyzes rapidly in the near ultraviolet. But on an Earth-like planet orbiting an M star, the N_2O abundance could be significantly higher because the flux of near-UV radiation would be much smaller. Figure 34 shows a spectrum of a hypothetical Earth-like planet orbiting the M star AD Leo. This atmosphere contains ~ 1 ppm of N_2O , along with more than 400 ppmv of CH_4 . The N_2O band at $8.5 \mu\text{m}$ is partly visible on the wing of the extremely strong $7.7\text{-}\mu\text{m}$ CH_4 band. A second band of N_2O at $17.7 \mu\text{m}$ might help one discriminate between the two species, if the TPF-I spectral range extends that far out in the infrared. Another potential biomarker gas, methyl chloride (CH_3Cl) is also visible, although its absorption bands overlap with O_3 and CO_2 . Both oxidized and reduced

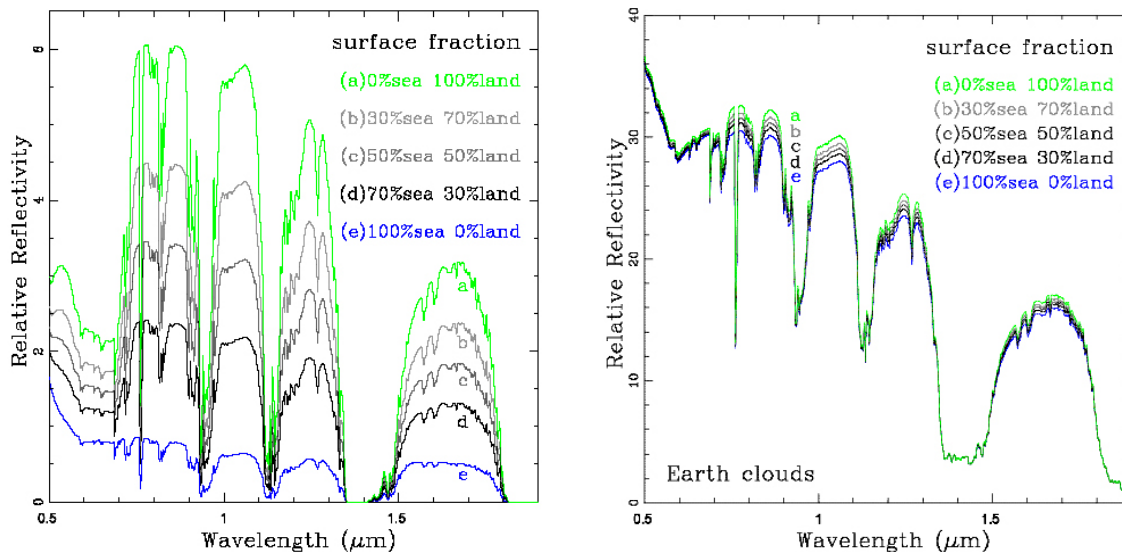


Figure 36. Signal of different surface fractions of sea on land for present-day Earth atmosphere, for several contributions of different kinds of surfaces assuming a clear atmosphere without clouds (left), with clouds (right). Note different scale. (Kaltenegger *et al.* 2006)

biomarker gases could conceivably be present simultaneously in the atmospheres of M-star planets, provided that some mechanism exists for distributing heat over the planet's surface. (Habitable planets orbiting M stars would become tidally locked on short time scales, and hence could have one permanently sunlit hemisphere and one permanently dark one.) The spectral signature of O₂ (or O₃), along with CH₄, N₂O, or CH₃Cl, would be powerful evidence for the existence of life.

The results of modeling, illustrated in Fig. 35, show the changes in detectability and shape of spectral features due to ozone, carbon dioxide, and methane for the “same” planet around stars of different spectral type. These observed changes in detectability are due to an interplay between the star's spectrum, the photochemistry of ozone, and coupled changes in the thermal structure of the planet's atmosphere. These models were run for host stars of F, G, K, and M spectral type.

Other biogenic trace gases might also produce detectable biosignatures. Currently identified potential candidates include volatile methylated compounds (like CH₃Cl above) (Segura *et al.* 2005) and sulfur compounds. Although it is known that these compounds are produced by microbes, it is not yet fully understood how stable (or detectable) these compounds would be in atmospheres of different composition and for stars of different spectral type and incident UV flux. (As shown in Fig. 36, even something as straightforward as the presence or absence of clouds and the extent of sea cover affect the measurable signal from an exoplanet.) These uncertainties, however, could be addressed by further modeling studies. Clearly, if we can expand the potential suite of detectable biogenic trace gases and understand the condition under which they are most likely to be detectable, we will gain more confidence in our ability to identify life remotely.

A dramatic case of surface biomarkers on Earth is the red edge signature from photosynthetic plants at about 720 nm. Around 440 million years ago, an extensive land plant cover developed, generating the red chlorophyll edge in the reflection spectrum. The exact wavelength and strength of the spectroscopic red

edge depends on the plant species and environment. Averaged over a spatially unresolved hemisphere of Earth, the additional reflectivity of this spectral feature is typically a few percent. The main diluting factors include forest canopy architecture, soil characteristics, non-continuous coverage of vegetation across Earth's surface, and the presence of clouds (which prevent a view of the surface). Modeling of different planet spectra, including the possibility of a different type of photosynthesis is essential to be able to interpret the detections. The signatures of different type of photosynthesis will be difficult to verify as biological through remote observations.

Expected Near-Term Progress

Weakly coupled photochemical/climate models have already been used to study problems such as the dependence of ozone and trace gas concentrations on atmospheric O₂ level and on stellar type. These models can be improved by incorporating more rigorous radiative transfer techniques, by more tightly coupling the atmospheric physical and chemical processes to produce self-consistent results, and by more realistically incorporating the effects of clouds on the climate and inferred detectability of planetary features. These models will provide the best available assessment of global planetary atmospheric composition, thermal structure, and detectability of atmospheric and surface characteristics of interest. They will also allow the exploration of terrestrial planet types different from those found in our own Solar System. In particular, it is important to develop models of how biogenic trace gas emissions are related to atmospheric constituent levels such as oxygen.

Contributions to Navigator Science

Global observations of Earth are proving useful in several ways. First, they have demonstrated the potential of spectroscopy for characterizing Earth-like exoplanets. Second, they form the basis for validating spectral models of the present-day Earth before they are applied to the Earth at an earlier age or to extrasolar terrestrial planets of different ages, different compositions, and orbiting stars different from the Sun. Finally, they provide a check on the required or preferred performance parameters of the TPF missions.

Satellite observations of Earth give insight into the variety of spectroscopic signatures of land, ocean, and clouds in different environmental conditions (location and different seasons of the year).

The modeling of planetary systems and terrestrial planets will improve our understanding of the potential range of habitable worlds, while providing the theoretical framework for the analysis and interpretation of TPF data. This research will also allow us to determine which gases, surface spectral features, and time-variable characteristics are potential biosignatures for extrasolar life.

6.4 Summary: Opportunities, Risk, and Priorities

Recommendations

Within the planetary-science and Earth-observing communities, there is a wealth of existing models and data that can be modified, augmented, or incorporated into planet-formation and volatile-delivery models, or in global models of terrestrial planet equilibrium states and evolution. These models, in the service of TPF science, can be used to explore the likely range of characteristics that will be observable for extrasolar

terrestrial planets, and they can help us better understand the detectability of these characteristics as a function of planetary composition and age, and the spectrum of the host star.

Advances in the next few years, that incorporate more detailed biogeochemical cycles into planetary models, will allow us to search for biosignatures beyond the current modern-day Earth-centric spectral suite of ozone, methane, chlorophyll, and leaf-reflectivity features. The development of these tools will greatly increase our ability to explore and assess detectability and likelihood issues for specific planetary and life characteristics as our knowledge of this field continues to evolve. Integrated planetary models would also allow us to characterize and understand the global appearance of Earth throughout its 4.6-Gyr of evolution, including the life-supporting Earth prior to the rise of significant amounts of atmospheric oxygen. Continued modeling will also allow us to better identify possible “false positives,” abiotic planetary characteristics that may mimic sought-for biosignatures in planetary spectra. In the short term, continued work to model planetary environments and their appearance to astronomical instrumentation will provide input to requirements for TPF instrumentation characteristics (such as sensitivity, spectral resolution, and wavelength range) that will work to maximize the likelihood of detecting and being able to characterize habitable and inhabited worlds.

Without these theoretical studies, we risk focusing only on those terrestrial characteristics and biosignatures that are understood via direct observation of Earth and other terrestrial planets in our own Solar System. However, Earth is potentially only one of many examples of a habitable world, and if we focus and design based only on a search for strictly Earth-like characteristics, we greatly reduce our chance of finding and recognizing other forms of habitable or inhabited worlds.

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7 Astrophysics and Exoplanets

The Navigator Program has a broad scope of science that includes galactic and extragalactic astrophysics in addition to exoplanets science. The ability to carry out general astrophysics observations follows naturally from the design requirements of the Navigator missions, which provide unprecedented high-angular resolution and high dynamic-range sensitivity.

The following are among the key questions that challenge and motivate future missions:

- What is dark matter?
- What is dark energy?
- How did the universe begin?
- How did the first galaxies form?
- How has the intergalactic medium evolved?
- How do the feedback cycles between galaxies and the intergalactic medium (IGM) work?
- When did the first black holes form, and how are black holes and galaxies related?
- How do stars form and what governs their mass distribution?

Such issues have been identified by the astronomical community in the National Academies studies – e.g., the McKee–Taylor decadal survey report *Astronomy and Astrophysics in the New Millennium* (2001), the Turner report of the committee on the physics of the universe *Connecting Quarks with the Cosmos* (2003), and in the NASA strategic roadmaps. Because of their unique capabilities, the Navigator Program missions will have an important role to play in helping to address these questions. In this chapter we focus on the space missions — SIM, TPF-C, and TPF-I. Space missions are a precious resource, and it is vital to consider the potential for general astrophysics as part of the design studies. Of its science time,* SIM PlanetQuest intends to allocate about 22% for planet-search Key Projects, 33% for astrophysics Key Projects, and 45% for competitive award through the Guest Observer and Legacy Programs. For TPF-C and TPF-I, roughly $50 \pm 10\%$ of the science time should go to core exoplanet science with $50 \pm 10\%$ devoted to general astrophysics.

Expected Near-Term Progress

It is not possible in this volume to summarize the expected near-term progress in all of the non-planetary fields that might be touched upon by exoplanetary missions. However, it is worth giving a flavor for the rapid progress, and expected limitations of current facilities, in a few key areas.

* The science time is the available observing time after accounting for grid-star observations and time required for engineering tasks.

Breakthroughs in our understanding of dark matter may well come from one of the direct-detection physics experiments planned or currently underway. If this happens, the astrophysical questions will change so fundamentally that it is difficult to predict the key questions. However, if existing experiments result in non-detections, astrophysical constraints on the properties of dark matter are extremely important. Over the next decade we can expect to see much more detailed mapping of the spatial density profiles of the baryon-plus-dark-matter halos represented by galaxies and clusters of galaxies. The density profiles and the amount of substructure provide critical tests of whether dark matter is warm or cold and whether it is non-interacting. Some of the most interesting constraints come from gravitational lensing. Constraints are currently limited by the paucity of known sources and the difficulty of obtaining precise measurements of lensed source positions, fluxes, and time delays. While much progress will be made with continued HST, JWST, and ground-based observations, it is possible that the structure of dark-matter halos will still be an important issue even when TPF-C is launched.

The study of dark energy is an emerging field, having been born in 1998 with the discovery of cosmic acceleration. New ways of measuring cosmic geometry continue to emerge. By 2010, samples of well-measured supernovae Ia (SN Ia) at $z > 1$ should have grown from ~ 10 to ~ 30 , although still very few will be known at $z > 1.5$. JWST, with increased sensitivity in the near-infrared, will allow studies to much higher redshift, providing an excellent handle on possible systematic effects from supernova evolution, and constraints on whether there have been multiple epochs of acceleration since recombination. In the meantime, uncertainties on the present day expansion rate H_0 may improve from 10% to better than 5% from further Cepheid measurements in SN Ia hosts with HST, and calibration against the direct maser distance to NGC4258. Ambitious attempts are underway to constrain dark energy from ground-based measurements of the imprint of acoustic oscillations on galaxy clustering (Bassett *et al.* 2005) and gravitational lensing. The evolution in the number density of rich clusters (probed by x-ray measurements, the Sunyaev-Zel'dovich effect, and gravitational lensing) will also provide valuable constraints, and we can expect progress in this area in particular from Planck, the South Pole Telescope, and the Large Synoptic Survey Telescope (LSST). The Dark Energy Task Force, set up to advise NASA, NSF, and DOE on strategies for exploring dark energy, recommends that *the dark energy program have multiple techniques at every stage*. If there are no fundamental physics breakthroughs in the meantime, it is likely that the astrophysical measurements conceived for SIM and TPF will still be critical at the time of the missions.

Our knowledge of the evolution of galaxies and black holes has seen tremendous progress over the past decade, as the redshift frontier has expanded to $z \sim 6$, and the intimate connection between black hole growth and galaxy growth has been revealed via the correlations between black hole masses and the properties of the surrounding stellar population. The redshift frontier will continue to expand with further observations by HST, Spitzer, JWST, and ALMA. These observations will very likely fill in the picture of the time-sequence of evolution from the first stars to the re-ionization of the intergalactic medium. If history is a guide, there may well be surprises that force us to re-think important aspects of current theories. Two important areas will remain relatively untapped by the time TPF-C launches: very high-resolution studies of galaxy structure at wavelengths $\lambda < 1 \mu\text{m}$, and statistical studies of very faint galaxies over wider areas than possible with JWST or ground-based adaptive optics. Very deep, high-resolution observations will become increasingly interesting as numerical models of galaxy evolution improve in resolution and start to incorporate the detailed physics of the interstellar medium and star formation. Wide-area surveys provide the statistical connection between the growth of galaxies and growth of dark-matter halos through measurements of clustering. The potential contributions of TPF-C in studies of galaxy evolution and the evolution of large-scale structure are critically dependent on TPF-C's field of view. The signal-to-noise

ratio of many of the statistical measurements increases linearly with the solid angle of the field of view. Parallel observations with a wide-field camera in parallel with the planet search are a particularly attractive way to increase the overall science return of the mission.

The strength of TPF-I is its unparalleled angular resolution, 12 mas at 7 μm , with a raw sensitivity equal to that of JWST. This will allow high angular resolution imaging of distant galaxies in the rest frame near infrared, where most of the light of the galaxies is emitted. Also for active galactic nuclei (AGN) studies, these capabilities are extremely valuable: the structure and dynamics of the enigmatic tori around nearby

Table 6. SIM PlanetQuest General Astrophysics Key Science Projects

Title of Project (Principal Investigator)	Abstract
The Search for Young Planetary Systems and the Evolution of Young Stars. (Charles A. Beichman, California Institute of Technology)	A study of the early stages of the formation of planetary systems around young stars that will provide new insight into how planets like Earth might have formed.
Stellar, Remnant, Planetary, and Dark-Object Masses from Astrometric Micro-lensing. (Andrew P. Gould, Ohio State University)	A novel technique of microlensing will be used to make exceptionally precise measurements of the masses of stars and a variety of other astronomical sources. Micro-lensing involves changes to a star's appearance that occur due to gravity from a nearby object.
Dynamical Observations of Galaxies. (Edward J. Shaya, University of Maryland)	By determining the precise distances and motion of nearby galaxies, this scientific program will study the formation of the local group of galaxies.
Astrophysics of Reference Frame Tie Objects. (Kenneth J. Johnston, U.S. Naval Observatory)	This program will obtain the data required to determine the motion of the Milky Way relative to extremely distant extra-galactic sources.
Anchoring the Population II Distances and Ages of Globular Clusters. (Brian C. Chaboyer, Dartmouth College)	This program will make observations to determine the ages and distances of globular clusters that are needed to determine the age of the universe.
Determining the Mass-Luminosity Relation for Stars of Various Ages, Metallicities and Evolutionary States. (Todd J. Henry Georgia State University, Atlanta)	Determine to an accuracy of one percent the mass of 100 main-sequence stars and a special sample of 100 additional field stars. The improved mass-luminosity relation derived from this work would impact many fields of astrophysics and could be one of the major accomplishments of the SIM mission.
Taking the Measure of the Milky Way. (Steven R. Majewski, University of Virginia)	A study of the motion of stars in our galaxy to determine the forces that cause the motion to understand better the distribution of matter in the Milky Way.
Binary Black Holes, Accretion Disks and Relativistic Jets: Photocenters of Nearby Active Galactic Nuclei and Quasars. (Ann E. Wehrle, California Institute of Technology)	A study of possible motions and changes in active galactic nuclei and quasars. The data will provide new and unique insight into the physical processes in these sources.

and very distant quasars will be mapped in exquisite detail, allowing their physical properties to be constrained and elucidating their role in helping forming massive black holes.

Our understanding of star formation continues to improve as we gain knowledge about the collapse of dense cores in molecular clouds, the formation of proto-planetary disks, proto-stellar outflows and their influence on the surrounding interstellar medium, and the influence of magnetic fields. Nevertheless, many questions remain. We do not completely understand the transport of angular momentum in protostars. We do not understand the fragmentation process in molecular clouds, and how or whether that fragmentation governs the initial mass function of stars. Most stars form in clusters, but we do not understand in detail the role of environment in regulating star formation. We have only a rudimentary understanding of the physics governing star formation on the global scale of entire galaxies. Over the next decade we can expect substantial improvements in our dissection of star-forming regions from high-resolution infrared observations provided by JWST, large ground-based telescopes equipped with adaptive optics, and ALMA. TPF-I, with its hundred-fold increase in angular resolution compared with JWST, will be able to make detailed maps of disks around forming stars. This will greatly improve our understanding of the interplay of planet formation, disk structure, and the formation of planetary systems.

7.1 Capabilities

Before discussing the possible general astrophysics objectives of the various missions, it is necessary to make some assumptions about their capabilities. These assumptions derive from existing design studies, but they are (of course) subject to change as techniques for studying exoplanets evolve. The key capabilities are listed below, along with some examples of the kinds of astrophysical measurements enabled by these capabilities.

- **SIM Wide-Angle Capabilities:**
 - Single-visit 40- μ as astrometry at magnitude $V = 19$
 - Single-visit 3.2- μ as astrometry at magnitude $V = 13$
 - Global astrometry grid accuracy of 3.5 μ as (grid star magnitude $V = 10.6$)

- *Types of measurements enabled by these capabilities:*
 - Parallaxes can be measured to 5% accuracy well past the galactic center
 - Distances to stars within 3 kpc can be measured to 2% uncertainty
 - Absolute calibration of RR-Lyrae and Cepheid period—luminosity relations
 - Accurate measurement of the stellar mass—luminosity relation
 - Greatly improved globular cluster ages

- **TPF-C Capabilities:**

- Point-source limiting magnitude $V = 31$ in 2 hours observation
- 15-mas resolution at $0.5 \mu\text{m}$
- Wavelength range 0.4 to $1.7 \mu\text{m}$
- Field of view of at least 10 square arcminutes
- 60- μas narrow-angle astrometry at $V = 25$ in 1 hour of observation

- *Types of measurements enabled by these capabilities:*

- Measure the globular-cluster-age main sequence turnoff in galaxies at 4 Mpc
- Resolve features as small as 200 pc in galaxies at redshift $z = 6$
- Measure rotation or transverse motions of 100 km/s in galaxies at 1 Mpc
- Measure the Cepheid period-luminosity relation in galaxies at 150 Mpc

- **TPF-I Capabilities:**

- Wavelength range 6–20 μm
- 20-mas resolution at $10 \mu\text{m}$
- 0.4- $\mu\text{Jy/pixel}$ at $12 \mu\text{m}$ in 10^5 seconds
- Field of view ~ 1 arcsecond at $10 \mu\text{m}$

- *Types of measurements enabled by these capabilities:*

- Obtain images of the dusty tori surrounding the black holes in active galactic nuclei
- Resolve features as small as 100 pc in the rest frame near-infrared for galaxies at $z = 10$
- Resolve dense protostellar cores in molecular clouds at a distance of 100 pc
- Construct infrared spectral maps of the extended atmospheres of nearby asymptotic giant branch stars

7.2 General Astrophysics Objectives

While the general-astrophysics programs of planet-finding missions will undoubtedly evolve prior to launch, it is worth summarizing some of the astrophysics objectives currently conceived for SIM, TPF-C, and TPF-I:

1. *Stellar Evolution.* SIM distance measurements to nearby stars and globular clusters will resolve one of the major impediments to accurate determination of the ages of stars. Measurements of stellar oscillations by Kepler and COROT will also test stellar-evolution models. If these observations and the subsequent refinement of models yield an absolute accuracy of better than 5% in the ages of the oldest stars, then stellar chronology will emerge once again as an important cosmological tool – testing dark energy models and/or models for early galaxy formation and re-ionization.

2. *Cosmology.* SIM will remove the major uncertainties in the lowest rungs of the cosmic distance ladder by determining precise distances to galactic Cepheids and RR-Lyrae stars and local-group galaxies. Cepheid observations of nearby SN Ia host galaxies with TPF-C could reduce the uncertainty in the Hubble constant H_0 to $\sim 2\%$, providing a critical test of dark-energy models. Both TPF-C and TPF-I will test galaxy-formation models via the highest-resolution measurements of the structure of high-redshift galaxies.
3. *Dark matter.* SIM will measure proper motions and rotational parallaxes of nearby galaxies, allowing a full reconstruction of galaxy orbits in the Local Group, thereby vastly improving our understanding of the distribution of dark matter within and around galaxies. TPF-C will be able to measure proper motions in more distant galaxies and will also probe dark matter through high-resolution images of gravitational-lens systems.
4. *Exotica.* SIM and TPF-C will measure the astrometric shifts induced by microlensing events that, combined with observations from the distant Earth, will allow the detection of isolated black holes toward and massive stellar remnants toward the center of our Galaxy. TPF-I will provide definitive measurements of the structure of the dusty tori that surround black holes in active-galactic nuclei.

For SIM in particular, some of the programs and investigators have already been selected. These are summarized in Table 6. Further details of these and conceptual projects for TPF-C and TPF-I follow.

7.3 Formation and Evolution of Stars

Fundamental Stellar Properties

Mass is the most fundamental characteristic of a star, and it is crucial to our understanding of stellar astrophysics that stellar masses be determined to high accuracy. SIM PlanetQuest will measure stellar masses with errors of 1% or less for roughly 200 stars, and will allow stellar astrophysics models to be challenged more severely than ever before. There are currently only ~ 40 stars with masses this accurately known, and 30 of these are components in eclipsing binary systems with masses between 1 and 3 solar masses. Thus, the range of our understanding of precise stellar masses is terribly limited. Many more stars at the high- and low-mass end of the stellar mass spectrum will be accessible to SIM measurements.

Stellar Accretion Disks and Jets

In the last 10–15 years our understanding of the formation of stars and planets has greatly increased, in large part due to improvements in spatial resolution (see Reipurth, Jewitt, and Keil, 2006, for a comprehensive review). The framework for the formation of low-mass stars (up to a few solar masses) is now well established. Condensations in interstellar clouds undergo gravitational collapse, leading to the formation of a star surrounded by an accretion disk. These systems often drive highly collimated jets and/or wider-angle outflows, which may play roles in the subsequent clearing of the remaining circumstellar gas and dust. This gradually reveals the star, first in the near-infrared and later in the visible.

Two key questions remain unanswered in this scenario: (1) what is the nature of the driving mechanism of the jet and to what extent is it responsible for the cloud-core dispersal, and (2) what is the structure of the accretion disk and, in particular, how does planet formation proceed in these disks? The steady flow of newly discovered extrasolar planetary systems makes this last question especially relevant.

TPF-I can make important and unique contributions to our understanding of star and planet formation. Its strength lies, of course, in the spatial scales that it opens up for investigation of 1 AU and less for low-mass young stars and their nascent planetary systems, and ~ 10 AU for regions of massive star formation. These scales correspond, respectively, to the terrestrial planet formation zone and typical close-binary separations. At these scales TPF-I will probe warm dust and gas (100–1000 K), which is strongly complementary to the colder (<300 K) matter that will be probed by ALMA on similar scales.

Milky-Way Globular Clusters

Observations of very distant galaxies represent a major focus of present research with the Hubble and Spitzer observatories, and are at the core of the James Webb Space Telescope (JWST) mission. These observations will give us tremendous insight into the first billion years of galaxy evolution, showing where and when the first stars began to form. However, the observations do not tell us where the first (or even second or third) generation of stars ended up.

SIM will improve distance measurements to globular clusters and the absolute calibration of the main sequence. Nevertheless, it is hard to predict the magnitude of the remaining uncertainties in absolute ages of the oldest stars in the Milky Way. Current theoretical models do not match the exact morphology of the main-sequence and sub-giant branches of globular clusters, suggesting problems with the theoretical treatment of element diffusion, semi-convection, and/or model atmospheres. The white-dwarf cooling curve provides an age estimate that is more sensitive to different physics than the main-sequence turnoff. Regardless of theoretical advances in the next decade, this is a crucial test of stellar evolution theory. The results for ages derived this way must agree with the results for ages derived from main-sequence fitting.

To date, the distance to only one cluster (M4) has been measured (with heroic effort) using HST, and a second more metal-poor cluster (NGC 6397) has just been observed, but no results are as yet available. By the time TPF-C flies, it is likely that several more will be done by HST and/or JWST. TPF-C can do the measurement with a few hours observing time out to ~ 7 kpc, which brings 32 globular clusters (and the galactic bulge) within reach. The field thus moves from a proof of concept to a tool for studying the demographics of globular clusters. Uncertainties in this technique are currently dominated by sampling statistics, bolometric corrections, distance uncertainties, and uncertainties in the chemical composition of the outer layers of the white dwarfs. TPF-C will reduce these uncertainties enough that ages to an absolute accuracy of better than 0.5 Gyr may be possible. With improved age accuracy, a comparison of the relative ages of the globular clusters will provide new and detailed insight into the star-formation history of the Milky Way within its first few billion years. This should help reveal whether globular clusters formed before or after reionization, and whether they primarily formed in situ or were accreted over time from other galaxies. A careful analysis of the luminosity distribution of cluster white dwarfs can yield the initial mass distribution of their progenitors.

Dynamical studies of globular clusters, which will greatly benefit from TPF-C and SIM astrometry, will yield valuable constraints on the neutron star and black-hole populations. Together, these observations will provide perhaps our best handle on the mass-function of this early generation of stars, which played a crucial role in the early chemical evolution of our galaxy.

TPF-C can provide an additional measurement of globular cluster ages by observing stellar oscillations on the stars near turnoff from the main sequence. As stars convert hydrogen to helium in their cores the separation of oscillation-mode pairs changes in a predictable way, allowing accuracies for age determinations of a few percent of the main-sequence lifetime. Only an 8-m class space-based telescope, observing for a period of 7–10 days, can provide the high throughputs needed to obtain stellar-oscillation frequencies in globular clusters by observing photometric variations of several parts per million to resolutions of one microhertz. This quite independent age determination, and more generally the availability of more observed quantities than theoretical parameters needed to model these stars, would allow for excellent consistency checks and challenges to stellar evolution theory.

Star-Formation Histories Beyond the Local Group

With HST it is possible, with major investments of observing time, to measure the main-sequence turnoff (MSTO) in any galaxy in the Local Group. This provides the gold-standard for estimating ages and metallicities. However, there are only two giant galaxies in the Local Group (the Milky Way and M31). All the rest are sub-luminous relative to the characteristic luminosity of galaxies (L^*). There are no giant ellipticals in the Local Group.

TPF-C will allow measurements of the MSTO in galaxies to a distance of 4 Mpc, a volume that includes more than 200 galaxies, including several L^* galaxies of various types in the Ursa Major and Sculptor groups. As currently conceived, TPF-C will provide significantly deeper measurements, in more crowded fields, than possible with JWST or ground-based 30-m telescopes. Measurements of a suitable statistical sample will indicate whether or not galaxies started forming stars simultaneously and will test our inferences from observations of high-redshift galaxies. These observations constrain the star-formation histories in the outer disks, outer bulges, and halos of galaxies, because even TPF-C will be limited by crowding in the inner regions.

Hierarchical cold dark matter (CDM) models suggest that the accretion of dwarf galaxies onto giant galaxies could be a way of building the stellar halos of galaxies. The Sagittarius dwarf and the M31 tidal stream are evidence that this process continues to the present, although it is unclear whether it is the dominant mechanism for creating halos. Horizontal-branch stars in halos can be detected to 10 Mpc, and the red-giant branch can be detected to 100 Mpc, enabling characterization of the spatial distribution and metallicities of halo stars in thousands of galaxies. Model predictions of these statistical distributions can only be tested by observations of a sufficiently large statistical sample of galaxies, which is not feasible with HST, but can be done with a few hundred hours of TPF-C observing time.

7.4 Formation and Evolution of Galaxies

While the current hierarchical paradigm of galaxy formation is spectacularly successful at reproducing the clustering properties of galaxies on large scales, there are potentially serious failures on small scales: discrepancies in the predicted galaxy luminosity function (particularly the relative numbers of dwarf and giant galaxies), difficulties in reproducing the number of massive old galaxies at high redshift and the number of strong submillimeter sources, difficulties in explaining the entropy of gas in clusters of galaxies, and difficulties in explaining the properties of damped Ly- α absorbers along the line of sight to distant quasars. It is clear that the theory of galaxy formation is still incomplete, and it seems likely that surprises will continue to emerge as our observations improve.

TPF-C will resolve substructure in galaxies; measure the clustering properties of distant galaxies as a function of size, stellar populations and morphology; and constrain the topology and time-sequence of re-ionization. While these topics will be addressed in part by HST and JWST, detailed study is likely to await TPF-C's greater sensitivity, better spatial resolution, and larger field of view. Because these are primarily statistical studies of field galaxies, the observations can be done in parallel with the planet search, provided the scattered background in the parallel camera field of view is sufficiently low and uniform.

Detailed studies of stellar populations in nearby galaxies (including the Milky Way and its satellites) are the natural complement to observations of high-redshift galaxies. Observations of Milky-Way globular clusters and resolved stellar populations in nearby galaxies are currently among the most challenging for HST and represent a significant fraction of the observing time. TPF-C will expand the accessible volume for such studies by more than an order of magnitude, allowing study of a range of galaxy types with different star-formation histories $SF(t)$.

Spitzer studies are showing the crucial role that IR observations are playing in understanding the formation of stars, galaxies, and AGN. A major problem however is the lack of significant spatial resolution, and this drawback will hardly be remedied by JWST. TPF-I will map out in exquisite detail the relevant formation processes, making it likely that a definite understanding of the formation of stars, galaxies, and AGN will be in within reach.

Structural and Dynamical Properties of the Milky Way

The high-precision astrometry offered by SIM PlanetQuest will provide key insights into the mass distribution of the various components of the Milky Way. Within the disk, efforts to determine the local mass density have been severely limited by the absence of a homogeneous, well-calibrated tracer population that can map the density and velocity distribution perpendicular to the plane. SIM will measure precise parallaxes and proper motions for 500 K giants within 20 degrees of the galactic poles, and it will provide accurate space motions for stars at distances up to 2 kpc above the plane. Crucially, these observations can be replicated for stars lying at radial distances of 1–2 kpc, allowing us to determine, for the first time, the non-local disk mass density.

At larger distances, SIM can measure the three-dimensional motions of distant halo stars, galactic globular clusters, and the satellite galaxies in the Milky-Way system. Their motions allow us to determine the Milky Way's total mass and its distribution, probing the contribution of dark matter to the galaxy's architecture.

Tidal streams, drawn from globular clusters and dwarf spheroidal satellites by gravitational interactions, are particularly sensitive probes of the symmetry and uniformity of the dark-matter halo. These systems will be observed as part of the SIM Taking Measure of the Milky Way Project. Their orbital motions are highly sensitive to substructure in the halo; therefore, they will test galaxy formation theories, particularly those tied to cold dark matter cosmologies.

Microlensing Studies of Objects in the Milky Way

More than 500 objects have been detected over the last decade in photometric microlensing experiments, where the lens betrays its presence by focusing (and so magnifying) the light from a more distant source. Unfortunately, the information that photometric microlensing yields about the lens is usually highly ambiguous. For example, about 15 microlensing events have been detected toward the Large Magellanic Cloud (LMC), but despite considerable effort, it is not yet known if these are due to a previously unknown stellar component of the Milky Way or to ordinary stars associated with the LMC itself. As another example, it is likely that about 150 of the 500 events detected toward the Milky-Way bulge are dark (brown dwarfs, white dwarfs, neutron stars, or black holes), but at present we have no idea as to which 150 these are. Even if we did, we would not be able to estimate their masses to better than a factor of 100 because only the timescale of the event is measured, and this is only one of the three parameters needed to determine the mass and distance to the star.

SIM PlanetQuest will revolutionize microlensing. Microlensing gives rise to astrometric deflections in the apparent position of the source, which are typically of the order of 200 μas . These are far too small to have been detected to date, but SIM will be able to measure them accurately to a few percent. SIM will make its measurements by counting photons as a function of fringe position, and thus its astrometric measurements are made at the same time as the photometric measurements. Since SIM will be in a solar orbit, it will see a significantly different event than is seen from the ground. By comparing SIM and ground-based photometry, it is possible for the mass, distance, and transverse speed of the lens to all be determined, often with a precision of 5%. SIM will be able to resolve the nature of the lenses being detected toward the LMC by measuring their distance, and so distinguishing between the Milky Way halo and the LMC for their location. By measuring the masses of objects in the galactic bulge, SIM will be able to separately identify the nature of each object and provide an inventory of the currently mysterious lenses detected toward the LMC and the non-luminous objects among the ordinary stars. TPF-C will be able to carry this work forward with fainter lensing events.

Evolution of the Internal Structure of Galaxies

TPF-C will provide a resolution of better than 100 pc for galaxies at any redshift. Neither JWST nor JDEM will approach these resolutions. Very large (20–30 m) ground-based telescopes with adaptive optics (AO) may achieve similar resolution over small fields in the infrared ($\lambda > 1\mu\text{m}$). However, TPF-C's gain over Hubble and ground-based AO is not just resolution: for typical L^* galaxies at redshift $z > 3$, studies of resolved structure are limited primarily by signal-to-noise ratio, even in the Hubble Ultra-Deep Field. (L^* is the luminosity typical of the Milky Way galaxy and M31.) Even with the vast improvements expected in AO, the giant ground-based telescopes planned for the next decade will suffer the same problem due to the high near-IR sky background. TPF-C will thus be unique in providing the most detailed view of the internal structures of distant galaxies, and will do this for samples of order 10^6 galaxies in narrow slices of

redshift. With this resolution and sensitivity, the study of galaxy evolution enters a new realm. Instead of modeling the global properties of barely resolved objects, star-formation histories can be constrained for many independent regions of individual galaxies. By this time, hydrodynamical simulations will be making believable, testable predictions for the internal structures of galaxies. Viewing galaxies with this resolution over a wide range of look-back times, we may finally be able to determine whether galaxies form from the inside out, the outside in, or primarily through mergers. With large statistical samples, it will be possible to determine whether star-formation occurs primarily in disks (punctuated by merger events), or primarily during the merger events themselves.

An essential constraint on galaxy formation models will be the spatial structure of very distant galaxies at 1–2 μm rest frame, the location of the peak of the spectral energy distribution of nearby galaxies. For distant galaxies, this region is redshifted into the spectral window within which TPF-I will be observing. Whereas JWST will hardly resolve these galaxies, the high spatial resolution of TPF-I will allow detailed mapping of a selected number of such galaxies.

Galaxies and Dark-Matter Halos

In contemporary theories of galaxy formation, galaxies form at peaks in the underlying dark-matter density field and reside in virialized dark-matter halos either as the central galaxy or as satellites orbiting within a larger halo. The observed properties of galaxies (such as color, morphology, or luminosity) depend on the mass and assembly history of their dark-matter halos. The environmental dependence of galaxy properties arises from their correlation with halo mass as well as the correlation of halo mass with collapse history and with the larger-scale density field.

Clustering measurements of galaxies are essential for making the connection between observations and hierarchical models. The models robustly predict the number-density of halos above a fixed mass threshold and the correlation function of those halos. Measuring the correlation function of galaxies thus establishes the mass scale for the dark-matter halos in which they reside. The comparison of the number-density of galaxies to the number density of halos indicates how many galaxies on average occupy each halo.

Clustering studies require large samples and large volumes. A grism survey with TPF-C could yield redshifts for more than 10^6 galaxies, with well-determined colors and morphologies from the accompanying broad-band imaging. Tracing the halo occupation distribution vs. redshift will test the paradigm that galaxies form at dark-matter density peaks, and it will allow us to trace the origin of the Hubble sequence back to the underlying dark-matter physics. TPF-C will complement efforts from the ground and JWST by providing the best measurements of position, luminosity function, and morphology and evolution of satellite galaxies orbiting within dark-matter halos at redshifts $z > 1$.

Quasar Science

The unprecedented astrometric accuracy and brightness sensitivity of SIM ($\sim 4 \mu\text{as}$ for $m_V < 20$) will allow, for the first time, the determination of the optical positions of extragalactic objects at the microarcsecond level, thus enabling a direct connection between the stellar and extragalactic frames. Extragalactic radio sources are known to have frequency-dependent intrinsic structure, usually consisting of a flat spectrum core with extended emission in the form of multiple steep-spectrum jet components, which may move

superluminally away from the core. (Superluminal motion is motion perpendicular to the line of sight with an apparent linear velocity in excess of the speed of light.) SIM PlanetQuest data taken on all SIM/International Celestial Reference Frame (ICRF) tie sources will be analyzed to search for systematic radio optical position offsets. These observations and the subsequent analyses will permit measurement of optical astrometric shifts and allow correlation with radio observations. Observation of systematic position offsets between the radio and optical emission in ICRF quasars would provide valuable insight into the physical mechanism(s) generating the radio and optical emission. SIM observations of extragalactic sources will be analyzed to search for optical photocenter wander. Optical photocenter wander can be used to search for binary black hole signatures.

TPF-C and TPF-I offer about a factor of 3 gain in resolution over HST and JWST. This could be very important for studies of quasars and AGN, as it increases the accessible volume at fixed physical resolution by a factor of 30. The distribution and dynamics of gas disks and flows on scales of a few parsecs or less can be investigated in the environments of supermassive black holes. In the unified model of AGN, an accretion disk surrounding a central black hole is surrounded by an optically thick torus of dust and gas that often hides the central region from our view, making the direct high-energy phenomena associated with the nucleus more difficult to observe. The orientation of the torus with respect to our line of sight determines whether we see the object as a Type I (Seyfert 1 or quasar) or Type II (Seyfert 2 or radio galaxy). TPF-I will be able to image the tori of very nearby AGN and resolve the tori of the most luminous AGN out to high redshift.

7.5 Cosmology, Dark Energy, and Dark Matter

Recent observations have improved our knowledge of the cosmological parameters greatly, but have also demonstrated that we understand very little about the underlying fabric of the Universe. Roughly 73% of the energy density of the Universe appears to be in the form of “dark energy,” which is causing the expansion of the Universe to accelerate. We do not know what dark energy is, how it relates to the known forms of energy, or how it relates to dark matter (which represents 23% of the mass-energy density of the Universe and is also poorly understood). Dark energy is often characterized by its equation of state $p = w\rho c^2$, where p is pressure, ρ is density, c is the speed of light, and w is a parameter that may be a constant or a function of time or expansion factor. The cosmological constant has a present-day $w_0 = -1$ and $w' = 0$, where w' is the time derivative of w . Concepts for measuring w_0 and w' have been widely discussed and debated. Constraining w_0 to better than ± 0.1 and w' to better than ± 0.2 appears achievable using high-redshift Type Ia supernovae. However, complementary approaches are essential to overcome systematic errors in any one technique. It is important that the complementary techniques achieve comparable levels of precision. The scope of the Navigator Program has the potential to achieve this with two distinct observing programs.

The Hubble Constant

Viable dark energy models must reproduce the fluctuations in the microwave background. With the CMB fluctuations held fixed, to measure the equation of state of the dark energy, the best complement to current and future CMB measurements may be a measurement of the Hubble constant that is accurate at the few percent level. SIM’s measurements of distances to Galactic stars and to the LMC should significantly

improve the local calibration of the distance scale. Further improvements in H_0 accuracy will require measurements of the distances to many more nearby host galaxies of Type Ia SNe and/or observations of primary distance indicators for galaxies distant enough to be moving with the Hubble flow. With its higher resolution and greater sensitivity, TPF-C will be able to detect Cepheids at 2.5 times the distance of Hubble, and its higher resolution will provide accurate measurements in fields too crowded for JWST. This will enable accurate distance measurements to more than 10 times the number of galaxies than currently possible, providing a better calibration of the absolute magnitude of Type Ia SNe, providing better control of systematics such as dependence on metallicity and reddening, and providing Cepheid distances for galaxies in the Hubble flow. Combining 2% uncertainties in H_0 with Planck's cosmic microwave background measurements should yield a precision of ± 0.04 in w from these observations alone.

Gravitational Lensing

With detailed modeling, the distribution of gravitational arc radii as a function of redshift in clusters of galaxies provides a measurement of the angular-diameter distance vs. redshift relation and an independent, purely geometrical, measurement of the effect of dark energy. The Planck mission is expected to detect roughly one cluster per square degree via the Sunyaev-Zel'dovich (S-Z) effect, and the Atacama Large Millimeter Array and the South Pole Telescope will add to that sample. By 2010, studies of this large, relatively unbiased, sample of clusters will be a major focus of observational cosmology.

Pointed observations with TPF-C will provide the deepest, highest-resolution observations of gravitationally lensed arcs and arclets in these clusters. Noise due to intervening large-scale structure, combined with uncertainties in the mass profiles of the lensing clusters, limits the usefulness of a single cluster. TPF-C will be able to observe a substantial sample of clusters with a modest investment of observing time. A photometric and spectroscopic grism survey of 50 clusters would yield hundreds of arc and arclet positions and redshifts as well as positions and redshifts for thousands of foreground galaxies. Combined with X-ray and velocity-dispersion constraints on the cluster mass profile, it may well be possible to achieve constraints on dark energy that are competitive with (and completely independent of) other proposed techniques.

The same observations will yield valuable constraints on the nature of dark matter. N-body simulations and analytical models suggest that dark-matter halos should have a nearly universal density profile, characterized by two power-law slopes and a scale radius. The ratio of the scale radius to the virial radius is expected to vary with halo mass, and show a distribution of values at fixed halo mass. The values of the parameters that describe halo profiles depend on the small-scale power spectrum and hence the nature of dark matter (e.g., whether it is warm or self-interacting). Measurements via gravitational lensing of the mass-density profiles of a large sample of S-Z selected clusters will thus constrain the nature of dark matter.

Measurements of strong lensing by individual galaxies will also provide important constraints on the nature of dark matter. The spectrum of density fluctuations in CDM has sufficient power on small scales that dark-matter halos in galaxies are expected to be lumpy. This lumpiness has been invoked to explain "flux anomalies" in several well-known gravitational lens systems. However, the extent to which the flux anomalies support CDM is hotly debated. With follow-up of large optical and radio surveys, we expect roughly 600 lens systems will be known by 2015, of which 10% will be useful for substructure tests.

TPF-C will provide precise positions and fluxes of the components of the lensed images, will provide grism redshifts for some of them, and will reveal faint additional images below the current limits of detection. Combined, this data set will allow a critical test of the substructure predicted by CDM theory on galactic scales.

7.6 Programmatic Issues

The importance of general astrophysics for the Terrestrial Planet Finder missions has been emphasized in the National Academy decadal survey *Astronomy and Astrophysics in the New Millennium* (2001) and in the *Review of the Science Requirements for the Terrestrial Planet Finder* (2004). The decadal survey, which considered concepts for an infrared interferometer, stated:

To ensure a broad science return from TPF, the committee recommends that, in planning the mission, comparable weight be given to the two broad science goals: studying planetary systems and studying the structure of astronomical sources at infrared wavelengths.

The 2004 committee, which focused more on TPF-C, concurred with the decadal survey on the significance of general astrophysics and encouraged the project to continue to develop the science case:

Yet although the proposed new camera for TPF-C possesses interesting capabilities, the associated science case has been neither carefully developed nor critically reviewed. The panel recommends that NASA solicit input from the astronomical community in order to develop the strongest possible science case.

The science case for TPF-C has evolved significantly over the past two years, and an instrument concept study for a wide-field camera has been completed. The TPF-C Science and Technology Definition team adopted the concept of open competition for 60% of the observing time on a 5-year mission, independent of scientific goals (which could include anything from follow-up studies of the detected exoplanets to cosmological studies of distant galaxies). The other 40% would be reserved for the core search and initial characterization of terrestrial planets, but would nevertheless include broad participation of the community through open competition.

It is a high priority to continue to refine the general astrophysics programs of both TPFs. This will occur through community workshops and involvement of general astrophysics advocates in Navigator Program committees. It is important that a more quantitative effort be made to understand the overlap and complementarities of possible TPF general astrophysics capabilities with other planned facilities. It is also important to further investigate both the scientific potential and the limitations of TPF-C observing in parallel with the TPF-C planet search. Focusing community attention on these issues will help to refine our understanding of the kinds of science programs that can be uniquely accomplished with the TPF missions.

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8 Programmatic Priorities

Preparatory science topics differ widely in their contributions to the Navigator Program, and they differ in when their contributions are needed. In this chapter, the preparatory science activities are highlighted according to priority, for their impact at different phases of the development of SIM PlanetQuest, TPF-C, and TPF-I. It is important to emphasize that this prioritization does *not* reflect any attempt to rank the *intrinsic scientific merit* of any of the research topics presented in this document. Instead, this prioritization is derived solely from the relative importance of scientific results insofar as they contribute to the various technical, scientific, and programmatic decisions during the different phases of the development of TPF-C and TPF-I.

8.1 Preparatory Science for SIM PlanetQuest

This section describes preparatory science that is specific to SIM PlanetQuest. The subjects that are of most interest here are those that relate to the calibration of measurements made by the interferometers that make up the SIM instrument, as well as target selection. This precursor science does not relate so much to the properties of planetary systems as it does to the properties of stars that are in some sense well-behaved, or predictable, and devoid of stellar companions. The understanding of scientific data that will lead to a new planet discovery is inexorably intertwined with understanding the physical properties and motions of stars located elsewhere in the sky.

Observational Programs of SIM PlanetQuest

SIM PlanetQuest is an astrometric mission with the capability of finding habitable planets through relative angular separation measurements of the positions of stars, and is a mission for discoveries of unique and fundamental astrophysics. SIM will improve by more than a hundred-fold upon the precision and accuracy of previous global astrometric measurements. This two-order-of-magnitude increase in accuracy presents the scientific community with a major challenge: very little is known about astrometric characteristics of stars at the few microarcsecond level. The consequent uncertainties make it difficult to design and optimize observing modes, methods, and calibration strategies. The success of this approach therefore depends not simply on precise measurements of relative angles, from one star to another, but also on the existence of a calibrated grid of stars that provides a fixed or well-characterized reference frame for the measurements.

SIM PlanetQuest has been engaged in a program of preparatory science since 1998. A tremendous amount of theoretical and observational effort went to four categories of stellar objects: target sources, grid stars, guide stars, and reference stars. Target sources include various dwarfs and pre-main-sequence (PMS) stars

for exoplanet search, and also a variety of X-ray binaries, globular clusters, black holes, and AGN for general astrophysics. Of particular need were investigations of grid stars, which provide accurate knowledge of baseline for SIM PlanetQuest. The grid is expected to be comprised of astrometrically stable objects with mean separations on the sky of about 4 degrees and no fainter than about 12th magnitude at V-band. Once proper motion and parallax are taken into account, an astrometrically stable object position that is suitable for inclusion in this grid should be reproducible to within 4 μ as. This requirement places potentially severe limits on stellar multiplicity, the presence of planetary or other circumstellar systems, and photocenter wandering arising from changes in source structure or appearance. SIM PlanetQuest has two guide interferometers and one science interferometer. The guide interferometers provide a stable baseline for the science interferometer. For each observation field of regard (15 degrees in diameter), two guide stars separated by about 90 degrees are needed simultaneously. SIM PlanetQuest has a wide-angle mode and a narrow-angle observing mode. The wide-angle mode can provide astrometric accuracy of 10 μ as, and the narrow-angle mode is for deep search of Earth-like planets with accuracy of 1–4 μ as. For narrow-angle mode it is necessary to have 4–6 nearby reference stars. The separations between target star and reference star must within 0.5–2 degrees. The smaller the separation between target and reference stars, the better the accuracy. The Preparatory Science Program for SIM PlanetQuest was focused on the four categories of stellar objects above. Many years of effort on the SIM PlanetQuest observation list has gone into theoretical and observation work. The number of targets is mainly limited by the mission life time (five years). The planning for SIM PlanetQuest has included a balance between planet searches and astrophysical studies. The details of these preparatory science programs are described in the following.

Target Sources

The SIM PlanetQuest mission has ten key projects. Three key projects concentrate on planet searches, and seven are oriented toward fundamental astrophysics. Target sources for planet searches are divided into three categories:

- About 2000 nearby dwarf stars, to search for Neptune or larger exoplanets (period < 10 y)
- About 250 close targets for deep search of Earth-like planets
- About 200 PMS sources to search for young and forming exoplanets (distance \sim 150 pc)

For exoplanet searches SIM PlanetQuest has an unprecedented high accuracy of 1 μ as, and unique capabilities to determine inclination and eccentricities of exoplanet orbits. The inclination of an exoplanet is the key parameter to determine the mass of an exoplanet. The eccentricity is a crucial physical parameter that may determine if it is habitable or not. SIM PlanetQuest will establish a new milestone for exoplanet searches. It will completely change the current status of exoplanets and provide new statistics of exoplanets.

There are about 20,000 candidate sources for astrophysics. Those sources will be used for the following research in astronomy and astrophysics:

- Spiral structure of the Galaxy
- Dynamics of the local group of galaxies
- Accurate age and distance of globular clusters
- Accurate mass of galactic black holes and X-ray sources

- Proper motion of nearby AGN sources
- Low-mass luminosity function
- Structure of quasars

Since the target stars for astrophysics have quite different spectral characteristics, it is necessary to do ground observations in advance in order to calibrate their spectral energy distribution.

Grid Stars and Extragalactic Sources

SIM will build its own precision reference frame using an all-sky astrometric grid for interferometric baseline determination. The all-sky astrometric grid is the cornerstone of mission operations. The grid stars will be observed periodically during the mission and use 25% of observation time. The grid stars will, for the first time in astronomy, establish a microarcsecond optical reference frame. This optical reference frame will be linked to an existing radio reference frame, the International Celestial Reference Frame (ICRF). Optical counterparts of a complicated radio source can be correlated with corresponding radio images to a precision of tens of microarcseconds.

In addition to galactic grid stars, SIM PlanetQuest will observe many extragalactic objects, nominally quasars, to establish a quasi-inertial anchor for the all-sky astrometric grid. The quasars will remove any residual rotation in the SIM reference frame. These distant sources are assumed to have negligible proper motions. In order to remove the rotation in the SIM stellar frame, we need to determine three angular velocity coordinates. In theory, only two fixed extragalactic objects (three coordinates total) could be used to determine the rotation of the SIM stellar frame defined by the grid stars. In practice, the structure of the reference sources and variable error propagation in the grid solution as well as possible zonal systematic errors dictate that a global distribution of extragalactic sources be used.

The ICRF consists of 212 extragalactic radio sources that vary in visual magnitude from 13 through 19. Observations of objects fainter than 16th visual magnitude with SIM will be difficult; they will take an excessive amount of observing time, as the stated accuracy of the SIM positions should be 4 μ as or better. To accomplish this, the positions must be determined to 4 μ as. Observation of the ICRF sources to an accuracy of 4 μ as will take a prohibitive amount of time since many of these objects are fainter than 17th magnitude. Observations of the optically brightest compact extragalactic sources rather than ICRF sources are suggested to determine the SIM frame rotation. These sources may or may not have radio emission. They should be brighter than 16th visual magnitude in order to insure that a large number of sources can be used to address calibration issues regarding possible source variability and structure. This is especially true since we do not know the structure of the optical emission of the extragalactic sources on size scales < 1 arc second or the variability of their emission.

The positional accuracy of the individual sources in the ICRF catalog is of order >250 μ as at radio frequencies. Thus to align the new SIM frame to the current ICRF, observations by SIM of the 212 defining sources need to be performed only to a similar level per source. The current plan, however, is not to observe the entire set of 212 stars. A reasonable integration time at this level of precision for 10 observations (five in each coordinate) of each source is proposed spaced over the mission duration. In this way, the relationship of the new SIM frame to the ICRF can be established at the accuracy of the ICRF.

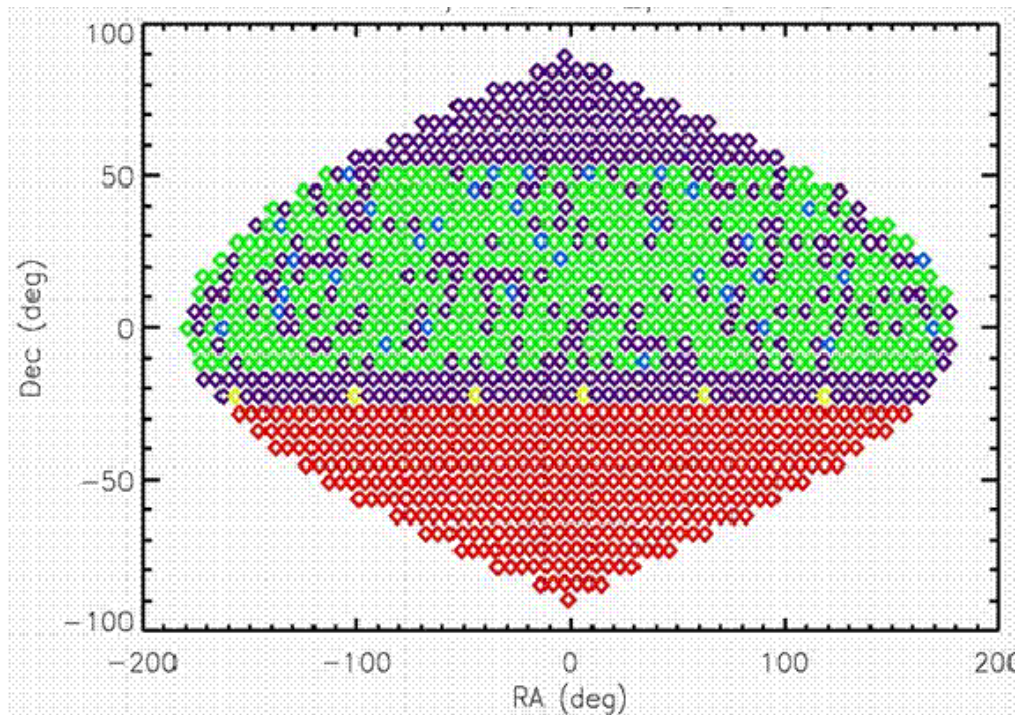


Figure 37. Coverage of grid star verifications, where the three colors correspond to the areas assigned to the three observing groups. (X. Pan, JPL)

Because little is known about the structural morphology of quasars on SIM scales, a program of precursor quasar observations is dictated. The U.S. Naval Observatory Flagstaff Station is currently observing twelve quasars as part of their optical parallax program. Preliminary results show a stability of 5 mas in position even for sources that display some structure on arcsecond scales at optical wavelengths. More complete observations are underway that will yield an evaluation of stability at the 1-mas level. Photometric observations are underway for a significant number of possible SIM quasars. It is planned to observe these sources annually for the next 5 years to ascertain their variability as well as to observe them during the year before and during the mission. Preliminary results indicate significant magnitude differences for numerous sources. It also appears that the sources are redder than expected. In addition, observations continue at radio wavelengths to strengthen the ICRF in the southern hemisphere. Observations are also continuing of the ICRF and other radio sources to study their radio structure and establish new radio sources that are brighter than 16th visual magnitude.

The grid will be comprised of astrometrically stable objects with mean separations on the sky of about 4 degrees. Approximately 1300 K-giant stars are required at about $V = 11.5$ mag or brighter. Once proper motion and parallax are taken into account, an astrometrically stable object position that is suitable for inclusion in this grid should be reproducible to within $4 \mu\text{as}$. This requirement places potentially severe limits on stellar multiplicity, the presence of planetary or other circumstellar systems, and photocenter wandering arising from changes in source structure or appearance.

Table 7. Priorities of SIM PlanetQuest during Phase C/D

Priority	Science Theme	Research Topic
1	Reference Stars	Grid stars; Guide stars; Reference stars
2	Target Stars	Target selection
3	Frequency of Terrestrial Planets	Observation Planning

The SIM Grid Star Verification Program is being carried out by three observing groups, selected via the Request For Proposals (RFP) issued by JPL. As shown in Fig. 37, three observing groups are working in three different colors to cover the full sky. Radial velocity measurements at several epochs are performed in these programs to detect orbital motions and remove those stars from the list of grid star candidates. The RFP was closed in April 2003. Observing began in August 2004 and is expected to continue for approximately 4 years. Details of the program are given in Appendix C.

Guide Stars

SIM has two guide interferometers and a science interferometer. The guide interferometers observe two bright objects separately in order to provide an inertially stable baseline for the science interferometer. Delay measurements from bright guide stars are fed forward to stabilize the science interferometer, allowing it to acquire and measure fringes on much fainter science targets. The guide stars requirements are:

- Brighter than 7–8 magnitude
- Must be “clean”
- Diameters less than 5 mas
- Stable to better than 1 μ as in an hour

Approximately 10,000 guide stars are selected from a total of 17,000 stars, which are brighter than 7th magnitude.

Reference Stars

Narrow-angle astrometry for exoplanet searches requires reference stars within 0.5–2 degrees from the target star. These nearby stars are a set of astrometrically stable reference stars, roughly evenly distributed across the sky. Narrow-angle observations produce relative, not absolute, parallaxes and proper motions. Their positions are measured relative to a small number of relatively bright reference stars, not to the astrometric grid. Several hundred K-giant stars are required, no fainter than about $V = 12$. The astrometric stability requirement, after fitting for position, parallax, proper motion, and linear acceleration, is 4 μ as RMS. This amount of jitter is substantially smaller than the expected accuracy of individual SIM measurements of stars.

Four to six bright reference stars will be needed within every 4-degree region of a science target. About 10 candidate reference stars will be chosen for each such science star. A sample of candidate reference stars will be selected by using infrared and visual narrow-band photometry and available parallaxes to identify candidate K0–M0 giants. This sample of about 500 stars will be reduced using narrow-band photometry to identify the K giants. Several subsequent steps are required to identify the best candidates.

- **Binary Stars:** Spectroscopy and adaptive optics will be used to eliminate binary stars. Adaptive optics imaging from large ground-based telescopes and HST snapshots will be used to search for close binary companions to target stars, rejecting stars with companions closer than ~ 100 AU. Most stellar binaries can be eliminated with just two radial velocity observations. The proxy study of K giants sets the astrophysically attainable Doppler precision to 20 m/s. However, this is a much higher precision than is needed to identify stellar companions. An initial Doppler precision of 50 m/s will be used to speed up identification of stellar binaries. This first filter can be done with 3-m class telescopes. Spectroscopy will also be used to identify spectroscopic binaries using 2–3 spectra to look for radial-velocity variability. Objects removed from the planet-search sample could be added to the fundamental properties sample.
- **Companions:** 10 years of the highest-precision Doppler observations will be carried out for the potential science target stars. These stars will have the best information regarding the presence of companions.
- **Chromospheric Activity:** The Ca, H, and K lines will be monitored for chromospheric activity, and abundance analyses will be carried out. To meet these goals, these stars will be observed more often and with higher than normal signal-to-noise ratio. This process of target identification can be absorbed into the ongoing program of radial velocity survey work.
- **Variable Stars:** Photometric monitoring of all potential science targets will be carried out to reject variable stars.
- **Disk Structure:** It may yet be possible that disks or other nebulosity will be a problem for possible science stars. 2MASS data and other near-IR data can be used to reject stars with massive accretion disks. The HST snapshot imaging sample could be expanded to investigate nebulosity or disk structures at the 0.1 arcsecond scale. Continued observing programs at Keck and Palomar could also be used to assess the presence of disks as well as binary companions using adaptive optics imaging.

The characterization of reference stars is part of the ongoing work contributing to the SIM Key Science Projects that deal most closely with planet-finding.

8.2 Preparatory Science for TPF-C and TPF-I

For the two Terrestrial Planet Finder missions, much of the preparatory science is common and is focused on understanding planetary systems and characterizing target stars. The missions will nonetheless observe in different wavelength bands, and research into biomarkers for each waveband will have a different emphasis. Because of the similarity of their objectives, the development of each mission is shown schematically by the single illustration in Fig. 38, which highlights the major project phases and gate reviews. In green, we indicate the most significant programmatic decisions that each mission must face. In the sections below, we describe in more detail how scientific questions feed directly into the decisions that TPF-C and TPF-I face during their development.

Pre-Phase A

In Pre-Phase A, the focus of TPF science will be to contribute to the Mission Concept Review that will allow a TPF mission to enter Phase A of its project lifecycle. Key questions will include the level of exozodiacal emission and its influence on the designs of interferometer or coronagraph architectures; an assessment, mostly complete, of the spectral markers for TPF; and an initial selection of appropriate target stars.

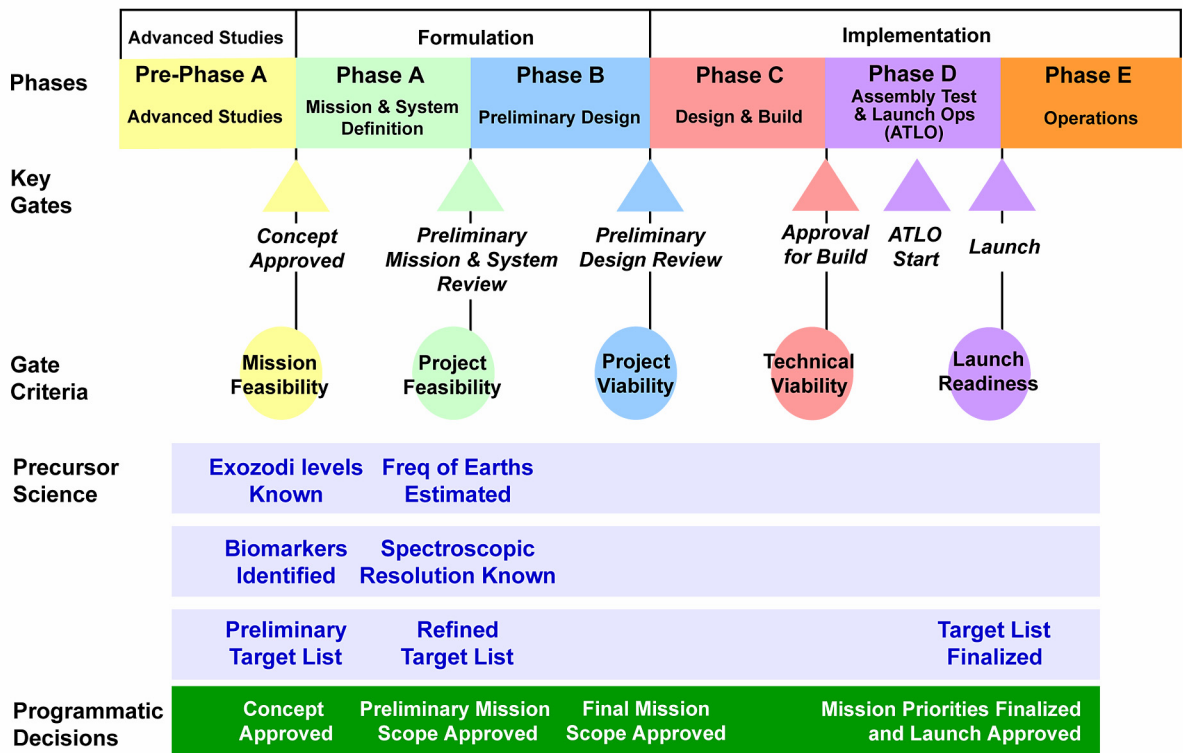


Figure 38. Summary schedule identifying the mission phases and science gates for the Terrestrial Planet Finder Missions.

Priority 1: Exozodiacal Dust

For the coronagraph and interferometer designs, the driving requirement is the need to suppress or reject starlight so that planet light can be detected. Moreover, atmospheric spectroscopy must be possible within the bands of biomarkers that have been identified. The TPF Project has estimated that starlight rejection of $\sim 10^9\text{--}10^{10}:1$ is necessary for optical coronagraphs, and $\sim 10^5\text{--}10^6:1$ for mid-infrared interferometers. In both cases the contrast ratio has been estimated based on an assumed brightness ratio of the star and planet. Previous architecture studies have shown that the brightness of dust in the habitable zone of the target star adversely affects the integration time necessary to detect planets for both the coronagraphic and interferometric systems, but with a somewhat greater effect for interferometers. Thus, in addition to a critical assessment of the technology needed for the two architectures, it is important to characterize and understand the brightness of the average exozodiacal emission surrounding potential target stars prior to the Mission Concept Review.

- A survey of a representative sample of target stars for dust on all orbital scales, from < 1 AU out to 100 AU, is important for both the mission concept review and selection of preliminary targets. Although selected stars may be studied through individual peer-reviewed proposals, a program coordinated between NASA and ESA is needed that will make the best use of missions such as Spitzer and Herschel.
- The TPF and Darwin Projects should also work to coordinate and make best use of upcoming ground-based facilities, such as the nulling instruments at KI and LBTI in the Northern Hemisphere and the VLTI in the Southern Hemisphere.
- Our understanding of levels of exozodiacal dust and its relation to the search for planets would be further bolstered by strong support for a wide-ranging program of theory and modeling.

Priority 2: Frequency of Terrestrial Planets

Improved knowledge of extrasolar planetary systems will allow us to predict with greater certainty the scientific return from TPF-C and TPF-I. This question has highest priority once each mission enters Phase A, and therefore should have a high priority in the preceding years.

- A comprehensive theoretical investigation into many aspects of the formation and evolution of planets and planetary systems must provide the framework within which to understand necessarily incomplete observational results. The combination of the existing and near-term radial velocity and transit programs—with theoretical insights into the orbital stability of planets, planetary migration, and the relationship between gas giants and rocky planets—will further enrich our understanding of extrasolar planetary systems.
- Our current understanding of the frequency of Earth-like planets is based on observations of higher-mass planets discovered through radial velocity surveys and on inferences from gravitational microlensing results. These highly successful programs should be further supported and encouraged as new detections of lower-mass and longer-period planets continue to refine our estimate of the frequency of Earths.
- Radial velocity surveys would be better supported through the development of new specialized high-resolution échelle spectrometers to offset the current demand for these instruments. Investments in

new equipment for radial velocity surveys, directed also at under-used 2–3-m class telescopes, would represent an excellent strategy in the development of workhorse instruments for exoplanet detection.

- Ground-based transit surveys that precede the space-based Kepler mission should also be encouraged. Of special interest is the development of a worldwide network of dedicated wide-field transit or microlensing search telescopes that would allow follow-up studies of bright targets.
- This investment in new survey equipment could be further leveraged if robotic observations were promoted at remote sites with excellent seeing conditions.

Priority 3: Target Stars

The quality of science that will be derived from TPF will be partly determined by the stars included in the final target list. A preliminary list of stars will greatly assist in judging the technical feasibility of the mission concepts. This preliminary target list may include a larger number of stars than are retained in the final list.

- The TPF project needs to determine which stellar parameters are most relevant to the search for life. These parameters, once known, will need to be monitored over time for the stars included in the target list. Spectroscopic observations over a broad range of wavelengths will be needed with coordinated access to appropriate space observatories run by NASA and ESA. The TPF and Darwin projects should work with NASA and ESA to ensure a coordinated observing program to observe target stars.
- The study of background fields of many target stars should be monitored in the years prior to TPF-C and TPF-I. Since many target stars will have large proper motions, imaging observations with HST done years in advance offer the prospect of identifying objects that may affect TPF observations, but which will be too close to the target to be separated on images taken at the epoch of either TPF-C or TPF-I.
- To complement the studies of nearby stars and potential targets, adequate support is needed for the development and maintenance of comprehensive databases and archives relevant to planet searches. A database, or central clearing-house, with active solicitations to provide missing information (colors, radial velocities, photometric variability, metallicities, binarity, interferometric measurements of diameters, etc.) should be established in Pre-Phase A.

Priority 4: Signs of Life

The technical requirements for the architectures of both coronagraphs and interferometers are dependent upon the wavelength range, or spectral bandpass, that is necessary to detect evidence of life. In particular, the shortest operating wavelength determines the required surface smoothness of optics and the mechanical stability of the observatory. The need for better starlight suppression would push the designs to use longer wavelengths, but amongst mid-infrared biomarkers the relatively short-wavelength water-vapor band at 6.3 μm may prove the most sensitive and easiest to interpret—forcing a tightening of requirements of a mid-infrared interferometer design. The necessary spectral bands of visible and mid-infrared biomarkers must be known if the design teams are to provide instruments tailored to TPF’s needs.

To explore the plausible range of terrestrial planets that we may find, it is important to create self-consistent theoretical models of planetary characteristics and evolution. These models will help to refine

the instrumentation requirements and search strategies for the TPF missions, and they will ultimately provide a theoretical framework for analysis of the mission data.

Phase A

In Phase A the emphasis will be on specifying the detailed design of the optics of each TPF observatory, TPF-C or TPF-I, leading to the Preliminary Mission and System Review. The mission and system definition studies will refine the architecture so that it is ready for preliminary designs in Phase B. The overriding question to be resolved by the end of Phase A will be to define the capability of the mission and determine to what scale the observatory must be built. What volume of space should be searched for planets? How large of a collecting area will be needed? What angular resolution will be required? Scaling the architecture and defining the scope of the mission will be necessary before either TPF-C or TPF-I continues to Phase B, C, and D.

Priority 1: Frequency of Terrestrial Planets

The scale of the TPF observatories—the size of the coronagraph primary optics or distance between the furthest collecting apertures of the interferometer—will determine the number of stars that are attainable by each mission. Defining the capability of a mission will involve a trade between the desire to explore a larger number of extrasolar planetary systems and the technological difficulty of building a larger observatory.

To better understand this trade, preparatory science activities *prior* to Phase A will include detections of planets by a variety of techniques. Coupled with advances in astrophysical theory, these data (including perhaps transit detections of several-Earth mass planets from COROT or MOST for nearby stars) will provide improved estimates of the frequency of Earth-like planets. The programmatic implications will be wide-ranging. More certain knowledge of the frequency of Earths will not only help set the scale of the observatories but will later assist in setting priorities in the initial phases of the missions.

Priority 2: Target Stars

The refined target list, to be developed for each mission during its Phase A, will assist in developing the trades (taking into account the expected performance limits) that will ultimately define the capability of TPF. The number of attainable target stars of different spectral types, their distances, and detailed characteristics will largely determine the scientific return of each mission. This target list is more than just an output from a catalog search. As explained in Chapter 5, there are many characteristics of stars that must be measured, and then carefully weighed in importance, before such a refined list can be constructed.

All nearby stars should be well characterized before the target lists for TPF can be chosen. A refined target list, with the farthest target identified, will be needed in Phase A to set the scale of the observatory. The distance to the farthest planet in the survey will be determined by the size of the observatory (its angular resolution) and the area of its collecting apertures (its sensitivity).

Table 8. Priorities of TPF-C and TPF-I Science Themes During Pre-Phase A and Phase A

Priority	Pre Phase A	Phase A
1	Exozodiacal Dust	Frequency of Terrestrial Planets
2	Frequency of Terrestrial Planets	Target Stars
3	Target Stars	Signs of Life
4	Signs of Life	Exozodiacal Dust

Priority 3: Signs of Life

In Phase A the details of the spectrometers, filters, dichroics, and operating wavelengths of various instruments within a TPF facility will need to be defined. The instruments will be optimized for the detection of known biomarkers. Our understanding of biomarkers must have advanced sufficiently during Phase A to set requirements for the detailed instrument designs.

The spectroscopic resolution is another key parameter that defines the scientific scope. Because the planet signals are very faint, the spectroscopic resolution translates very directly into a sensitivity requirement. How long does it take to perform spectroscopic follow-up of a significant number of detected planets? The resolution needed is, of course, a question that must be answered using our best understanding of the geophysical, atmospheric, and astrobiological processes that may be present on planets that TPF detects. The details of the studies needed are laid out in Chapter 6.

Priority 4: Exozodiacal Dust

Observations to characterize exozodiacal dust will continue to be important during Phase A and also in the phases through launch. Activities in this science theme will contribute to characterizing the stars in the list of target stars.

Phases B and C/D

In Phase B, C, and D, preparatory science will emphasize the preparation of a mission whose capability is already well defined. Studies will emphasize further development of the target list, understanding the environment of the target stars, and determining the best strategy to maximize the scientific return of the mission.

A coordinated program will continue to observe and characterize all potential target stars and to establish a standardized database and archive of measurements. The target lists will be refined and prioritized to identify target stars most likely to harbor Earth-like planets. Observations with SIM PlanetQuest will be a particularly important component of this final step of characterization.

Up until launch, preparatory science activities will aid in preparations for each mission: undertaking complementary observations of the target stars, establishing databases of standardized measurements, and refining techniques for the detection of biomarkers. There will be a wide variety of activities focused on improving the scientific productivity of the missions.

8.3 Supporting and Related Science Programs

A robust and diverse program of research and analysis should be supported to advance the field of planet finding over a broad front. Results from these efforts will assist in providing a sound framework for interpreting current observational results and those that may be expected over the next several years. Individual projects each contributes to the overall picture. The larger ensemble of activities enriches the Navigator Program and trains a cadre of scientists ready to undertake future challenges of TPF-C and TPF-I. The following activities serve as examples of possible topics in ancillary preparatory science:

1. Observations of protoplanetary disks and young stellar objects with ground-based adaptive optics or space-based coronagraphy.
2. Planet and brown dwarf searches targeted at stars of earlier and later spectral types than are likely to be amongst the core targets for TPF.
3. Theory and modeling of habitable planets in unusual environments, such as around close binary or multiple stars, or as satellites of gas-giant planets.
4. Simulations and models of the dynamics of planetary interiors and how the dynamics affect the habitability of terrestrial-type planets.

In this chapter, the precursor science subjects related to SIM PlanetQuest, TPF-C, and TPF-I were ranked according to their priority during each phase of a mission lifecycle. Supporting and related activities are as a whole ranked lower in programmatic importance than the themes of previous chapters, and no attempt is made here to provide a relative ranking. Their lower programmatic ranking does not imply that these subjects are of less intrinsic merit, but simply that decisions related to mission architecture and design are not obviously dependent on these subjects.

9 Exoplanet Funding Opportunities

This chapter highlights the research opportunities that are available through NASA and in particular through the Navigator Program. The range of supporting activities in 2005–2006 is as follows:

- SIM Science Team
- TPF-I Science Working Group (SWG)
- TPF-C Science and Technology Definition Team (STDT)
- Coordinated activities and science planning with the European Space Agency
- Workshops and conferences, e.g., Protostars and Planets V; Cool Stars 14
- New science instrumentation, e.g., new radial velocity instruments

These activities contribute to growing the community of scientists engaged in Navigator-related research. Input and guidance from the scientific community is provided at the meetings of the TPF-C STDT and TPF-I SWG. These meetings emphasize the development of the scientific objectives and priorities for the missions, but they also provide for community engagement and oversight of progress with TPF-C and TPF-I. A broader network of scientists is also being fostered through coordinated activities with the European Space Agency. Most noteworthy among these activities is the TPF/Darwin conference series that brings together over 200 scientists from both the United States and Europe. The Navigator Program also co-sponsors workshops and conferences that have scientific objectives closely related to the goals of its mission. Although the above activities provide a forum for participation in the Navigator Program, direct funding by the program is provided by two principal sources, described in this chapter.

- Michelson Fellowship Program
- TPF Foundation Science, NASA Research Announcement (NRA)

Ongoing funding for Navigator science is provided within the TPF Foundation Science NASA Research Announcement (NRA). This is particularly important because it provides a mechanism for peer-review and directed funding emphasizing the research within the themes outlined in this document. Young researchers, in the early stages of their careers, are provided support through the Michelson Fellowship Program to engage in new science and technology programs related to exoplanet research.

9.1 Michelson Fellowship Program

The Michelson Fellowship Program is coordinated by the Michelson Science Center on behalf of the Navigator Program. The program includes an annual series of fellowships for young scientists and engineers working in disciplines related to exoplanetary research. Fellowship recipients receive financial support to conduct research at a host institutions in the U.S. for a period of up to 3 years (subject to annual review). To show the breadth of the program, a brief summary of the fellowships and beneficiaries is given here. Note that due to changes in the NASA budget, there were no new fellowships in 2006. New awards will resume in 2007.

Michelson Postdoctoral Fellows

Michelson Postdoctoral Fellowships are awarded annually, and each fellowship covers a competitive stipend (approximately \$54,500 for 2007 fellows) at a research institution in the US. The application deadline is typically in November for start of funding in September the following year. Michelson Postdoctoral Fellowships are initially awarded for 2 years with an optional extension for 1 additional year (subject to review). In addition to the research stipend, the awards cover benefits and institutional overhead. Each postdoctoral fellow receives a research budget (\$15,000 per year for 2007 fellows) to cover publications charges, travel, equipment, and other research-related expenses. Michelson Postdoctoral Fellows from 1999 to 2005 are listed below.

Ruslan Belikov, Princeton University (2005)
Michael Ireland, California Institute of Technology (2005)
Amaya Moro-Martin, Princeton University (2005)
Jennifer Patience, California Institute of Technology (2004)
Sean Brittain, National Optical Astronomical Observatories (2004)
Christopher Tycner, United States Naval Observatory (2004)
Jason Aufdenberg, National Optical Astronomical Observatories (2003)
Pascal Bordé, Harvard-Smithsonian Center for Astrophysics (2003)
Andrew Digby, American Museum of Natural History (2003)
Ettore Pedretti, University of Michigan (2003)
Remi Soummer, Space Telescope Science Institute (2003)
Brian Kern, California Institute of Technology (2002)
Jajadev Ragagopal, University of Maryland (2002)
Neda Safizedeh, California Institute of Technology (2002)
Philip Hinz, Steward Observatory, University of Arizona (2001)
Sam Ragland, Harvard-Smithsonian Center for Astrophysics (2001)
Jean-Philippe Berger, Harvard-Smithsonian Center for Astrophysics (2000)
Marc Kuchner, Harvard-Smithsonian Center for Astrophysics (2000)
Maciej Konacki, California Institute of Technology (2000)
Rafael Millan-Gabet, Harvard-Smithsonian Center for Astrophysics (1999)

Michelson Graduate Student Fellows

Michelson Graduate Student fellowships are awarded annually. The application deadline is typically November for start of funding in October the following year. Each graduate student fellowship covers 3 years of graduate research at a university in the U.S. In 2007 the fellowship will cover a graduate student stipend, an education allowance of \$10,500 per year, and a small research budget (up to \$7,500 per year for 2007 Fellows) to cover page charges, travel, equipment, and other research related expenses. Graduate student fellows from 1999 to 2005 are listed below.

Margaret Moerchen, University of Florida (2005)
 Eric Nielsen, University of Florida (2005)
 Nicole Putnam, University of Florida (2005)
 Deborah Howell, Massachusetts Institute of Technology (2004)
 Julien van Eyken, University of Florida (2004)
 Fergal Mullally, University of Texas, Austin (2004)
 Amir Give'on, Princeton University (2003)
 Wilson Liu, University of Arizona (2003)
 Marshall Perrin, University of California, Berkeley (2003)
 Josh Eisner, California Institute of Technology (2002)
 Survath Mahadevan, Pennsylvania State University (2002)
 Matthew Muterspaugh, Massachusetts Institute of Technology (2002)
 Chien Peng, University of Arizona (2002)
 Julie Wertz, Massachusetts Institute of Technology (2002)
 Rebecca Masterson, Massachusetts Institute of Technology (2001)
 Chad Ogden, Georgia State University (2001)
 David Berger, Georgia State University (2000)
 Douglas Hope, University of New Mexico (2000)
 Alice Liu, Massachusetts Institute of Technology (2000)
 Yuan Liu, State University of New York at Stony Brook (2000)
 Philip Hinz, University of Arizona (1999)
 Benjamin Lane, California Institute of Technology (1999)
 Erin Sabatke, University of Arizona (1999)

Michelson Educational Awards

The Michelson Educational Awards are aimed at supporting undergraduate and graduate education, and specifically educators and institutions in the preparation and presentation of educational material relevant to Navigator Program science (e.g., exoplanet research) and/or technology. The 2007 awards are anticipated to be in the range of \$35,000 to \$75,000. This is a relatively new component of the Michelson Program. The awardees to date are listed below.

Ben Oppenheimer, American Museum of Natural History (2005)
 James P. Lloyd, Cornell University (2005)
 William Heacox, University of Hawaii (2004)

9.2 TPF Foundation Science

The Terrestrial Planet Finder Foundation Science program is an element of the NASA Research Opportunities in Space and Earth Sciences (ROSES) solicitation.^{§§§} This is an annual NRA for basic research proposals to conduct scientific investigations in support of the Terrestrial Planet Finder. For reference, Appendix C lists all the TPF Foundation Science proposals funded since the NRA's inception in 2002. The listing in Appendix C provides a comprehensive view of the community interests in planet finding as well as an overview of the balance of subjects funded through projects in the Navigator Program. Although the TPF Foundation Science NRA will most likely *not* be offered in January 2007 due to disruptions in the 2007 budget, the program is expected to resume in 2008.

The scope of TPF Foundation Science includes the following: i) the scientific data and theoretical framework required to define the nature and scope of each TPF mission; ii) the scientific data and theoretical framework required to refine the target star lists; and iii) the theoretical background required to plan the missions and to interpret the data obtained. The TPF Foundation Science NRA covers many of the topics discussed in this document, specifically calling out the following tasks:

- Searches for planets by means of any proven technique (e.g., radial velocity measurements, transits, microlensing, high-contrast imaging) around a variety of types of stars, including solar, low and high mass, young, and highly evolved.
- Characterization and theoretical understanding of gas-giant planets found around other stars.
- Observational and/or theoretical studies of the composition and dynamics of zodiacal and exozodiacal dust, including evidence for cometary material around stars.
- Theoretical and/or observational investigations of the properties of the early Solar System as it may have related to the formation and evolution of habitable environments.
- Theoretical studies relevant to obtaining a more accurate estimate of the fraction of solar-type stars that may harbor terrestrial planets in the habitable zone, including studies of planet formation and migration scenarios in a variety of environments, as well as investigations of dynamical stability of various orbital configurations.
- Measurement of the properties of potential target stars to assess their suitability for the interpretation of TPF results. (Note that while a long term program of new observations and theory may be required to determine and/or derive these properties, such activities may be possible only via other NASA programs such as the Spitzer Space Telescope or the Keck Interferometer; however, it is outside the scope of the TPF Foundation Science program to solicit proposals for new observations with these other NASA facilities, proposals for which are solicited through other program announcements.)
- Development of a long-term archive of the key observational data and derived parameters in a manner readily usable by the larger community of interested researchers.

Proposals to this program may also include the development of facilities and/or instrumentation that directly enable the proposed execution of any proposed activities, subject to budgetary constraints. An

^{§§§} <http://nspires.nasaprs.com/external/>

interesting example of a funded proposal, particularly well-suited and useful for the TPF missions, is the StARS database (Ali *et al.* 2005), described next.

Example of a Funded Proposal: Stellar Archival and Retrieval System (StARS)

Each astrophysical property of a star has an influence on the existence and longevity of a circumstellar habitable zone. A particularly important preparatory activity therefore is the systematic compilation of information on nearby stars. Recognizing the importance of this activity, NASA is funding the development of the Stellar Archival and Retrieval System (StARS)**** through the TPF Foundation Science NRA. StARS is being developed as a long-term, user-friendly National Virtual Observatory compliant archive of all relevant data for stars on the candidate target list for TPF-C and TPF-I. The intent is for this archive to (a) gather all currently available, published observational data for these stars into an easily accessible database; (b) provide a capability to derive useful physical properties of the target stars (e.g., estimated ages, effective temperatures, space motions); and (c) provide a means to archive spectra and imaging data obtained for the TPF candidate stars in response to this and future TPF Foundation Science NRAs. The archive interface will be optimized to serve the needs of both the scientists and engineers who are designing the TPF instruments and the observational astronomers who are working to select the final target list. The archive design is modeled along the lines of the highly successful NASA/IPAC Extragalactic Database (NED). Like NED, quality control is enforced by including published, refereed data and by providing users access to all values if multiple estimates exist in the literature. Much of the software development is leveraged from proven technology developed and employed by NED and the InfraRed Science Archive (IRSA). A notable difference from NED is that the user interface is developed with JAVA, in order to allow users to interact conveniently with the archived data. The underlying database and user interface are designed so that they can be easily cloned or extended in order to provide a similar service for other projects such as SIM PlanetQuest.

Along similar lines, NASA should support other preparatory activities to include archives of relevant datasets. NASA's archiving of HIRES data from the Keck telescopes is an excellent first step in this direction. The long-term nature of radial velocity and astrometric searches for planets demands careful curation of data so that astronomers can apply a variety of algorithms or combine multiple datasets to improve the estimation of parameters or set more stringent limits. Similar arguments may apply to other NASA-supported data sets, e.g., non-Keck radial velocity studies and ground-based transit or microlensing searches. These databases, services, and similar archives should be put in place in the near-term to support and to take advantage of TPF-related research with Spitzer, KI, LBTI, and SIM.

**** <http://StARS.ipac.caltech.edu>

9.3 Additional Sources of Funding

Although funding for most aspects of this research are beyond the direct control of the Navigator Program, the questions that need to be addressed are forefront research activities likely to be allocated time and supported through NASA and other funding agencies such as ESA and the National Science Foundation. These sources of funding are discussed in this section.

Science Support Through Large Missions

Many of the observational programs that have been identified will be carried out through facilities already funded separately by NASA. We assume that the large missions (e.g., HST, Spitzer, SIM, and JWST) have their own support for science, and that TPF investigators using those facilities will compete for time and be supported through peer-reviewed proposals.

Support Through the National Science Foundation

The National Science Foundation funds research and education in most fields of science and engineering. It does this through grants and cooperative agreements to more than 2,000 colleges, universities, informal science organizations and other research organizations throughout the United States. The Foundation accounts for about one-fourth of federal support to academic institutions for basic research. Possible funding opportunities related to planet finding are as follows:

1. The **Astronomy and Astrophysics Research Grants (AAG)** program provides individual investigator and collaborative research grants for observational, theoretical, laboratory and archival data studies in all areas of astronomy and astrophysics. This includes research in Stellar Astronomy and Astrophysics: Studies of the structure and activity of the Sun and other stars; the physical properties and composition of all types of single and multiple stars; compact objects and their interactions; the formation and detection of extrasolar planetary systems; star formation and stellar evolution; stellar nucleosynthesis; and the properties of atoms and molecules of relevance to stellar astronomy.
2. The **Advanced Technologies and Instrumentation (ATI)** program provides grants to support the development and construction of state-of-the-art detectors and instruments for the visible, infrared, and radio regions of the spectrum, including interferometric imaging instrumentation and adaptive optics, and the application of new hardware and software technology and innovative techniques in astronomical research.
3. The **National Optical Astronomy Observatory (NOAO)** is a national center for research in ground-based optical and infrared astronomy. NOAO's purpose is to provide the best ground-based astronomical telescopes to the nation's astronomers, to promote public understanding and support of science, and to advance all aspects of U.S. ground-based astronomical research. As a national facility, NOAO telescopes are open to all astronomers regardless of institutional or national affiliation. Observing time on NOAO facilities is available on a competitive basis to qualified scientists after evaluation of research proposals on the basis of scientific merit, the capability of the instruments to do the work, and the availability of the telescope during the requested time.
4. **NSF Astronomy and Astrophysics Postdoctoral Fellowships (AAPF)** provide an opportunity for highly qualified young investigators within 3 years of obtaining their PhD to carry out an integrated

program of independent research and education. Fellows may engage in research of observational, instrumental, or theoretical nature, in combination with a coherent educational plan for the duration of the fellowship. The program supports researchers for a period of up to 3 years with fellowships that can be taken to the institution or national facility of their choice. The program is intended to recognize young investigators of significant potential, and provide them with experience in research and education that will establish them in positions of distinction and leadership in the community.

5. The **Antarctic Aeronomy and Astrophysics Program** supports studies of three major domains, including astronomy and astrophysical studies of the Universe. Astrophysical studies are primarily conducted at Amundsen-Scott South Pole Station or on long-duration balloon flights launched near McMurdo Station.

Support Through NASA Research Announcements

Many of the research activities described here naturally fall within the scope of NASA Research Announcements as part of NASA's Research Opportunities in Space and Earth Sciences (ROSES). The research announcements most closely related to TPF are as follows:

1. **Astrobiology Science and Technology Instrument Development and Mission Concept Studies (ASTID):** Develop instrumentation capabilities that will help meet Astrobiology science requirements on future space flight missions. In addition, the development of laboratory instruments designed to open a new area of study for Astrobiology will also be considered.
2. **Astrophysics Data Program (ADP):** Research involving NASA space astrophysics data that are currently archived in the public domain.
3. **Exobiology (EXB):** Research to understand the origin, evolution, and distribution of life in the Universe, including the pathways and processes leading from the origin of a planet to the origin of life.
4. **Long-Term Space Astrophysics (LTSA):** Long-term support, up to a maximum of 5 years, to enable investigations of appropriately large scope that are substantial and cohesive. This includes topics related to main sequence stars and the formation of protoplanetary disks and debris disks.
5. **Origins of Solar Systems (OSS):** Research related to (a) the formation and early evolution of planetary systems, (b) fundamental research and analysis necessary to detect and characterize other planetary systems, and (c) definition of the scientific performance of possible future space missions that would perform spectroscopy of exoplanets.
6. **Planetary Atmospheres (PATM):** Scientific investigations that contribute to the understanding of the origins and evolution of the atmospheres of planets and their satellites, and of comets. The characterization of atmospheres of exoplanets is included in the scope of this activity.
7. **Astronomy and Physics Research and Analysis (APRA):** Basic research related to investigations relevant to NASA's programs in astronomy and astrophysics: (a) develop detectors that may be proposed as candidate experiments on future space flight opportunities, (b) science investigations whose completion requires the flight of instruments as payloads on suborbital sounding rockets, stratospheric balloons, or longer-duration flight opportunities, (c) develop supporting technology, laboratory research, and/or conduct ground-based observations directly applicable to space astrophysics missions.

8. **Terrestrial Planet Finder / Foundation Science (TPF/FS):** Investigations that provide (a) scientific data and theoretical framework required to define the nature and scope of the TPF missions, (b) the scientific data and theoretical framework required to define the target lists, and (c) the theoretical background required to plan the missions and interpret the data obtained.

9.4 Conclusions

Active funding for exoplanet research in support of Navigator missions should be maintained and strengthened in the coming years. It is vitally important that the development of Navigator missions, and their operation as scientific observatories, be guided at all times by the best scientific consensus understanding of the field of exoplanet research. This is especially important, of course, for TPF-C and TPF-I when they are actually observing, but making the best use of available knowledge is important at all times. This represents one of the larger programmatic challenges that the Terrestrial Planet Finder missions must face, given their very long development period. We can expect great scientific advances during these years, and the missions must appropriately factor this new knowledge into their development. Helping to begin that process of adaptation is one of the main objectives of this document.

9.5 References

Ali, B., Stauffer, J., Ramirez, S., *et al.*, “The stellar archive and retrieval system,” *Bull. Am. Astron. Soc.* **37**, 1409 (2005). Abstract only.

<http://StARS.ipac.caltech.edu>

Details of the Michelson Fellowship Program can be found at the website of the Michelson Science Center

<http://msc.caltech.edu/michelson/>

Information on NASA research opportunities through the Science Mission Directorate can be found at

<http://nspires.nasaprs.com/external/>

Information on research grants through the National Science Foundation can be found at

<http://www.nsf.gov/funding/>

Appendices

Appendix A

Synergy of Navigator Missions

Navigator Space Missions and Ground-Based Projects

The missions in the Navigator Program work together to understand the nature of nearby planetary systems, and to explore them to search for terrestrial planets with life-supporting atmospheres. The search will focus on the stars nearest to our Sun, out to a distance of about 60 light years. The closer a planetary system is to us, the more information we can discover through techniques of high-angular resolution sensing and high dynamic range imaging. A number of different measurement approaches and mission architectures have been developed to carry out these very challenging measurements. These are described briefly here.

Keck Interferometer

The Keck Interferometer (KI) is a ground-based interferometer located at the summit of Mauna Kea, Hawaii. It has as its primary goal the characterization of exozodiacal dust around nearby stars, and the detection of hot Jupiter-like planets. It is designed to explore the dust distribution close in to a star (0.1–1.0 AU), in many cases nearer to the star than the region of the habitable zone.

KI combines light from the twin 10-m Keck telescopes. By using the light-collecting area of the world's largest optical telescopes, KI greatly increases the sensitivity available to optical interferometry. The subsystems of the interferometer include adaptive optics, laser metrology to control optical delay lines, and fringe tracking to measure the interference in the combined light from the two telescopes. KI achieved the first-fringes in 2001, and in August 2005 it yielded an interferometric null of 1 part in 100, a milestone in the development of planet-finding technology. Publically competed science observing with the KI nulling mode will begin in 2007.

Large Binocular Telescope Interferometer

The Large Binocular Telescope Interferometer (LBTI) is a ground-based interferometer currently under development by the University of Arizona and is located at Mt. Graham, Arizona. Its science objectives are similar to those of the Keck Interferometer, as it will examine and describe the dust and planets around nearby planetary systems, as well as detect Jupiter-like planets in orbit within these systems. The LBTI is complementary to KI because it explores regions of other planetary systems that are more remote from a star (1.0–10 AU). LBTI and KI will thus work together to fully describe the environment and the hottest planets in nearby systems.

The LBTI uses two 8-m class telescopes mounted on a single alt-azimuth mount. Because of its unique geometry and relatively direct optical path, the LBTI offers a science capability that is different from other interferometers. Its most notable difference is its ability to provide high-resolution images of many faint objects over a wide field-of-view. Science operations are expected to begin in 2008.

SIM PlanetQuest

SIM PlanetQuest is a pathfinder in the development of space-based interferometry. The mission combines the light from two 30-cm structurally-connected telescopes separated by 9 m. It will use precise measurements of fringe position to determine orbits of planets with a mass 0.5–5.0 times that of Earth around 220 of the closest stars. If every star had an Earth-twin orbiting in the star’s habitable zone, then SIM could detect six of these Earth-twins; if the planet’s mass were twice Earth’s mass, SIM could detect 30 of them. Around at least 15 stars, the detectable planets would be considered Earth twins. It will also perform a broader survey of over 2000 stars to look for planets the size of Neptune and larger.

In addition, SIM PlanetQuest will have the ability to make key contributions to the advancement of other areas of astrophysics, including searching/measuring the following: an astrometric search for brown dwarfs; masses and evolution of stars in close binary systems; accurate masses of low-mass binary stars; astrometric signatures of MACHO microlensing events; internal dynamics and ages of globular clusters; and the mass distribution in the halo of our galaxy, as well as its spiral structure.

The technology developed for SIM will see direct applications in the Navigator missions that follow. In August 2005, the last of its eight technology milestones was accomplished. Brassboard hardware of key technology will be completed and tested prior to beginning full implementation in order to reduce technical and cost risk during the implementation phase.

Terrestrial Planet Finder Coronagraph

TPF-C will search nearby Sun-like stars for Earth-like planets capable of supporting life. It will look for atmospheric signatures of water, molecular oxygen, ozone, and other chemical indicators of life.

TPF-C is envisaged as a large space telescope operating at visible wavelengths, with an elliptical primary mirror 8×3.5 m in diameter. This single-aperture coronagraphic architecture was chosen for observing in the visible spectrum because the angular resolution required can be achieved on a realistic primary aperture, and the wavefront precision required across the aperture can be implemented in a coronagraph design. It will have the most precise optics of any telescope ever built. It will be deployed beyond the Moon’s orbit for a mission life of 5 years, possibly extended to 10 years. TPF-C is now in Pre-Phase A of its development.

Terrestrial Planet Finder Interferometer

TPF-I has the same broad scientific goals as TPF-C and will be designed to be capable of measuring the atmospheres of nearby exoplanets. It is being envisaged as an infrared interferometer, using free-flying space telescopes, because a single telescope would need to have a primary mirror between about 40 and 100 m in diameter. At wavelengths of about 7–17 μm , TPF-I will search for the presence of water vapor, ozone, carbon dioxide, and methane.

Several specific architectures are still under study by NASA and ESA under agreements that may lead to a future collaboration for the mission. In the architecture studied by NASA, TPF-I would include five formation flying spacecraft: four 4-m class mid-infrared telescopes, and one combiner spacecraft to which the light from the four telescopes would be relayed to be combined and detected. As with TPF-C, TPF-I would be deployed in an Earth-Sun L2 orbit beyond the Moon. TPF-I is also in Pre-Phase A of its development.

Michelson Science Center

The Michelson Science Center (MSC) is a science operations and analysis center that supports numerous Navigator Program missions. It supports science software development, science operations, and the engagement of the science community. The MSC coordinates the Michelson Fellowship Program and Michelson Summer Workshop series. The MSC is based at the California Institute of Technology and builds on experience gained from the Infrared Processing and Analysis Center and the Spitzer Science Center. The MSC currently supports the Palomar Testbed Interferometer, the Keck Interferometer, SIM PlanetQuest, NASA Keck single-telescope operations, LBTI, and the Michelson Program.

Synergy of Navigator Missions

The exploration of extrasolar planetary systems is a rich and diverse field. It calls for measurements with many kinds of instruments, as well as theoretical studies and numerical modeling. To discover and characterize exoplanets that are habitable and may show signs of life, and to be sure beyond a reasonable doubt that we can detect life, we need to measure the statistical distribution of planet diameters, the masses of nearby planets, and the spectra at visible and infrared wavelengths. The missions that can carry out these measurements are Kepler, SIM, TPF-C, and TPF-I. Each of these missions is a vital element of the overall program of planet finding. Not only does each mission by itself provide its own compelling science, but together these missions form a coherent approach that will advance our understanding better than any single one by itself.

The characterization of exozodiacal dust is an important part of our understanding of other planetary systems. The Spitzer Space Telescope currently has a program of observing nearby stars to see how bright their infrared background is, and in so doing to provide a catalog of data of potential target stars for planet search missions. The stars near our own Sun will also be studied in detail by the Keck Interferometer (KI) and the Large Binocular Telescope Interferometer (LBTI) to reveal giant planets and dust in the inner regions of these systems. These two interferometers are complementary because they are sensitive to different angular scales on the sky around stars.

Our search for life will extend outward to about 60 light-years from us, and in this space we will first need to understand and characterize the planetary systems that exist there. This is not work that will have been accomplished by any other mission, since the transit detections by Kepler are only for those rare occasions when a planet's orbit passes directly across the line of sight to a star. For that reason, Kepler's success is dependent upon a search through a much larger volume of space.

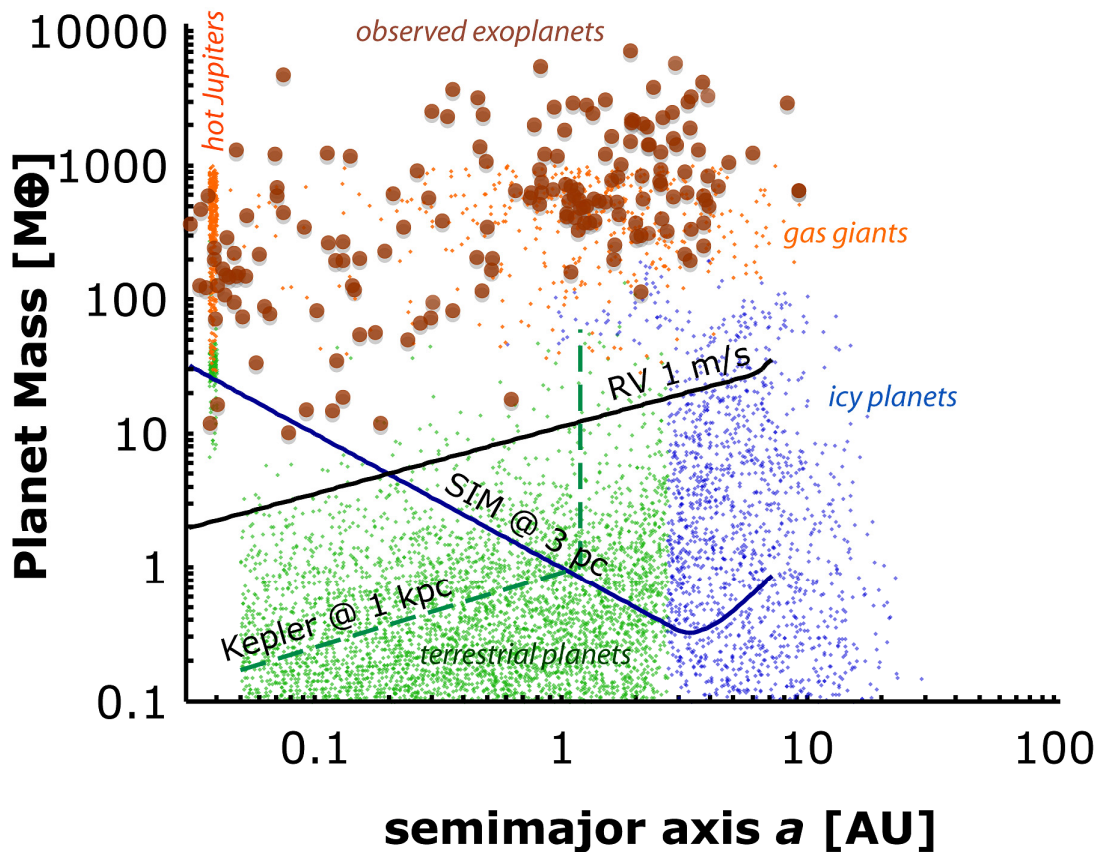


Figure 39. Detailed view of the discovery space for rocky Earth-like (~ 1 – 10 Earth-mass) planets in the habitable zone. All exoplanets that were discovered up until mid-2006 are represented by the larger filled circles (brown). The smaller dots represent a theoretical distribution for planets of 1–1000 Earth-masses (Ida and Lin, 2004). The simulations show the following types of planets: *gas giants* (orange dots) having an envelope mass at least 10 times the mass of the central core; *terrestrial planets* (green dots) initially formed within the ice line (2.7 AU for a solar luminosity star); and *icy planets* (blue dots) initially formed outside the ice line. The detection limits of radial velocity (RV) surveys, the Kepler transit photometry mission, and SIM PlanetQuest are also shown. The simulated planets have a distribution that mostly lies beyond the limits of radial velocity surveys (1 m/s); many such planets would nonetheless be accessible by Kepler (to determine their statistics), and by SIM PlanetQuest (to directly measure their orbits and masses).

The Navigator Program has as one of its goals an exhaustive planet search through our immediate neighborhood with SIM PlanetQuest as a precursor to other missions. The discovery space for SIM is shown in Fig. 39. SIM will be capable of detecting planets as small as one Earth mass, and will be able to measure orbits in exquisite detail. Our ability to predict the stars and planetary systems that might support life will be greatly advanced with the results of this mission.

The Terrestrial Planet Finder Coronagraph (TPF-C) at optical wavelengths, and the Terrestrial Planet Finder Interferometer (TPF-I) at mid-infrared wavelengths, will look for oxygen, ozone, water vapor, methane, and carbon dioxide. In the correct ratios, and observed over a broad wavelength range, these gases mark the existence of an atmosphere such as our own—changed by the presence of life. Through

numerous measurements at different epochs, TPF-C and TPF-I will be capable of providing unambiguous detections of Earth-like planets and evidence of the habitability of other worlds.

After TPF-C and TPF-I are successful, yet larger observatories will likely follow their lead, having an enhanced sensitivity, and thereby enabling higher-resolution spectroscopy. A comprehensive catalog of atmospheric constituents may then be obtained, and even time-varying spectra of atmospheric conditions measured across several seasons of planetary change.

The goals of the Navigator Program at NASA are to find Earth-like planets around nearby stars, to determine if they are habitable, and to search for signs of life. Three strategic missions are planned to carry out this program: the SIM PlanetQuest, the Terrestrial Planet Finder Coronagraph (TPF-C), and the Terrestrial Planet Finder Interferometer (TPF-I). These missions, along with the PI-class Kepler project, will each discover unique new knowledge about exoplanets, synergistically building on the other missions. This appendix outlines the scientific contributions of these missions, and the scientific synergies among them. We show that the scientific results from SIM are vital to maximize the return from TPF-C and TPF-I.

More than 200 exoplanets have been discovered since 1995. The vast majority of these planets were detected using Doppler spectroscopy instruments that are sensitive to large, massive objects like our Solar System's giant planets. Other types of instruments will be needed to detect small, light objects like Venus, Earth, and Mars, local examples of "terrestrial planets." NASA and the U.S. astronomy community currently plan to fly four distinct missions to search for terrestrial planets. This set of missions is designed to return maximum scientific benefit, and in particular to tell us, beyond reasonable doubt, if nearby planets can be found that are habitable and show signs of life.

For maximum scientific impact, each mission should be launched as soon as it is technologically ready. The scientific impact will be reduced substantially if fewer missions are launched.

Missions to Detect and Characterize Exoplanets

Kepler will detect planets by measuring the dimming of a star when a planet crosses in front of the stellar disk. Kepler will tell us the size of the planet, and the length of its year, using the measured depth and periodicity of dimming. It will do this with a 1-m class telescope, staring at a single field of (mostly distant) stars for several years. Kepler will be most sensitive to planets that are close to their stars, a key to telling us about planet formation and migration. Since it looks at more than 100,000 stars and is expected to detect hundreds if not thousands of planets, Kepler will tell us for the first time about the relative numbers of terrestrial planets in the habitable zone of Sun-like stars—something about which we can only guess today.

SIM will detect planets by measuring the wobble of a star back and forth across the sky. SIM will tell us the mass of each planet, its orbital distance, its orbital shape and orientation, and the length of its year. SIM uses interferometers to measure stellar positions with respect to neighboring stars, and it repeats these measurements over the full sky many times over several years. SIM will be most sensitive to planets that are massive and have periods of several years. For stars in the solar neighborhood, SIM will go well beyond the range of radial-velocity techniques, and will tell us which nearby stars have such planets, as

well as the relative numbers of heavy- and light-weight planets, down to about the ~ 1 Earth-mass range for the closest stars.

TPF-C will detect and characterize planets directly by measuring a visible-wavelength snapshot image of a star-planet system. TPF-C suppresses starlight to the level where the planet stands out clearly. TPF-C will be able to tell us the visible brightness of each planet, its orbital distance, its orbital shape and orientation, the length of its year, and the amounts of life-related atmospheric gases (oxygen, water vapor, ozone, carbon dioxide, methane). In favorable cases, TPF-C potentially will be able to tell us the length of the planet's day, the amount of plant life on the surface, an estimate of ocean/land ratio, and a measure of cloud variability. TPF-C uses a single, large-aperture telescope and a coronagraph to suppress starlight. TPF-C will be most sensitive to Earth-like planets in the habitable zone that are in orbital positions such that their day-lit portions are visible from Earth. TPF-C will be able to observe planets that are, on average, smaller than the planets that Kepler, SIM, and radial-velocity techniques can reveal. TPF-C will be designed to search for habitability and signs of life on exoplanets.

TPF-I is the infrared analog to TPF-C. TPF-I will detect and characterize planets, using the planet's own infrared emission, independent of the orientation of the day-lit side. TPF-I will measure an infrared snapshot image of a star-planet system in which the stellar infrared emission is suppressed to the level where the planet will stand out clearly. TPF-I will be able to tell us the infrared brightness of each planet, its orbital distance, its orbital shape and orientation, the length of its year, the amounts of life-related atmospheric gases (water vapor, ozone, carbon dioxide, methane, and nitrous oxide). If the planet's atmosphere is transparent enough, TPF-I may be able to tell us the length of the planet's day, an estimate of ocean/land ratio, and a measure of cloud variability. TPF-I uses an array of four formation-flying large, cooled telescopes and a nulling interferometer to suppress the star's infrared emission. Together, TPF-C and TPF-I are a scientifically ideal pair to search for habitability and signs of life on exoplanets.

Mission Connections and Synergy

The four missions—Kepler, SIM, TPF-C, and TPF-I—approach the search for terrestrial planets from different perspectives, and all perspectives are needed to determine habitability and search for signs of life. Kepler will examine distant stars in our Galaxy, a different set than the nearby stars the latter three missions will observe. Kepler will provide η_{\oplus} , abundances of terrestrial planets as a function of size, orbital period, stellar type, and stellar metallicity. This will assist in the design of TPF and target star selection.

Focusing on SIM, TPF-C, and TPF-I, all of which will examine many of the same target stars and planets, we show in Table 2 (Chapter 2) the important physical parameters that each mission can address. A check mark in the table indicates that a parameter can in principle be measured by one mission alone. A diamond indicates that multiple missions will be used cooperatively to determine a parameter. We anticipate that the strongest scientific statements about exoplanet characteristics will come from these cooperative measurements.

Stable Orbit in Habitable Zone

Each mission can measure an orbit and determine if it lies within the habitable zone (where the temperature permits liquid water on the surface of the planet). SIM does this by observing the wobble of the star, and

calculating where the planet must be to cause that wobble. TPF-C and TPF-I do this by directly imaging the planet and noting how far it appears to be from the star.

A SIM detection of a terrestrial-mass planet could provide TPF-C and TPF-I with targets to be characterized and the optimum times for observing them, thus increasing the early-mission characterization yield of TPF-C or TPF-I.

Where SIM finds a planet, of any mass, in almost any orbit, TPF-C and TPF-I will want to search as well, because we expect that planetary multiplicity may well be the rule (as in our Solar System and thus for detected exoplanets). Thus, SIM will help TPF-C and TPF-I to prioritize likely target stars early in their missions.

For cases where SIM detects a planet only marginally, an important cooperative aspect is that we could use TPF-C or TPF-I to focus on the system, and verify or reject the detection. Such verification could improve the uncertainty in SIM results.

Planet Temperature

A planet's effective temperature can be roughly estimated by noting its distance from its star, and by assuming a value for the albedo. TPF-C can make a better estimate of the temperature by noting the distance, and using planet color to infer its albedo (by analogy with planets in our Solar System). TPF-I can observe directly the thermal infrared emission continuum at several wavelengths (i.e., infrared color), and use Planck's law to calculate the effective temperature. For a planet with a thick or cloudy atmosphere (like Venus), the surface temperature is different from the effective temperature, but might be inferred from a model of the atmosphere.

With all three missions combined, the orbit, albedo, and greenhouse effect can be estimated; and the surface temperature as well as temperature fall-off with altitude can be determined cooperatively and more accurately than with any one mission alone.

Temperature Variability Due to Distance Changes

Each mission alone can observe the degree to which the orbit is circular or elliptical, and thereby determine if the temperature is constant or varying. In principle TPF-C and TPF-I can tell whether there is an asymmetry in color or spectrum at points in the orbit, and estimate a tilt of the planet's axis, which would also lead to temperature variability due to seasons.

The measurement of a terrestrial planet's orbital eccentricity using combined missions (SIM plus TPF-C and/or TPF-I) can be much more accurate than from any one mission alone, because complementary sensitivity ranges in planet mass and distance from star combine favorably. SIM will yield eccentricity data for the planets that it measures. This will aid TPF-C and TPF-I in selecting optimum observation times for measuring the temperature, clouds, and atmospheric composition of the largest terrestrial planets.

Planet Radius

SIM measures planet mass, from which we can estimate radius to within a factor of 2 (assuming a value of density, which in the Solar System spans a factor of 8). TPF-C measures visible brightness, which along

with an estimate of albedo, can give a similarly rough estimate of radius; a TPF-C color-based estimate of planet type can give a better estimate of radius. TPF-I measures infrared brightness and color temperature, which with Planck's law gives a more accurate planet radius.

Planet radius and mass, or equivalently density, is very important for determining the type of planet (rocks, gas, ice, or combination), its habitability (solid surface or not; plate tectonics likely or not), and its history (formed inside or outside of ice line). With SIM's mass, and one or both TPF brightness measurements, we can dramatically improve the estimate of planet radius.

Planet Albedo

The albedo is important because it controls the planet's effective temperature, which is related to its habitability. SIM and TPF-C combined can estimate possible pairs of values of radius and albedo, but cannot pick which pair is best (see above). We can make a reasonable estimate of albedo by using TPF-C to measure the planet's color, then appealing to the planets in our Solar System to convert a color to an absolute albedo. By adding TPF-I measurements we can determine radius (above), then with brightness from TPF-C we can compute an accurate albedo.

SIM and TPF-C together give a first estimate of planet albedo. Adding TPF-I gives a conclusive value of albedo, and therefore effective temperature and potential habitability.

Planet Mass

For the largest terrestrial planets, SIM measures planet mass directly and accurately. TPF-C and TPF-I depend entirely on SIM for planet mass. For smaller terrestrial planets, where TPF-C and TPF-I may not have a SIM value for planet mass, they will use theory and examples from our Solar System to estimate masses (see above).

SIM plus TPF-C and TPF-I are needed to distinguish among rock-, ice-, and gas-dominated planet models. This combination of observations will provide strong constraints on the habitability of a planet.

Planet Mass Sensitivity

To see how SIM can help TPF-C, we use a single target list of stars. For each target star, we calculate the minimum detectable mass of a terrestrial planet in the middle of the habitable zone. (These calculations are detailed in the addendum near the end of this appendix.) To illustrate the effective low-mass working range for each mission, we arbitrarily select the 25-percentile planet mass point (e.g., target number 35 in a ranked list for each case), and find a value of 3.9 Earth-masses for SIM, 1.1 Earth-masses for TPF-C, and sub-Earth-mass (not yet available) for TPF-I. Therefore SIM will typically be able to find heavy-Earth planets, pointing the way for TPF-C and TPF-I to find Earth-mass and Mars-mass planets.

We can understand these mass values qualitatively, as follows. SIM can most easily detect a stellar wobble when the planet is heavy, and the instrument's astrometric threshold is sufficiently small. TPF-C can most easily detect a planet when it has a large reflecting surface area per unit mass (i.e., smaller diameters), and the instrument contrast threshold is sufficiently small. TPF-I can have a smaller inner working angle than TPF-C, and so could see planets closer to the parent star. Several synergies result:

1. SIM will detect super-Earths and determine their orbits, giving TPF missions a list of relatively bright targets to study, along with optimum observation times.
2. SIM may find very massive planets in orbits that would make it impossible for a terrestrial planet to exist in the habitable zone. This information will be extremely useful for developing observing priorities for TPF-C and TPF-I.
3. Since SIM can survey many stars relatively quickly, it can produce a list of stars where habitable-zone planets are strongly or even marginally detected, and hand off this list to TPF-C and TPF-I for follow-up confirmation, and later characterization, thereby increasing the early-mission efficiency of the TPF missions.
4. For SIM detections, TPF-C and TPF-I can confirm the detection and measure the planet's colors, to build up a catalog of exoplanet properties.
5. For SIM detections that have low signal-to-noise ratios, TPF-C and TPF-I can improve the orbit parameters.

Surface Gravity

The planet's surface gravity is calculated directly using mass from SIM and radius from TPF-C and TPF-I (see above).

Surface gravity is important to habitability because massive, dense planets are more likely to have plate tectonics (a crucial factor in Earth's evolution). Surface gravity also determines whether a planet can retain an atmosphere (also crucial for Earth). Cooperative measurements are the only way to obtain this data.

Atmosphere and Surface Composition

The TPF missions are designed to measure a planet's color and spectra, from which we can determine the composition of the atmosphere and surface. For the atmosphere, TPF-C can measure water, molecular oxygen, ozone, the presence of clouds for a planet like the present Earth; in addition it can measure carbon dioxide and methane for a planet like the early Earth or a giant planet. For the surface, TPF-C can measure vegetation using the "red edge" effect (see below). TPF-I will add to this suite of observations by measuring carbon dioxide, ozone, water, methane, and nitrous oxide using different spectroscopic features, and in general probing a different altitude range in the atmosphere. SIM is important to this interpretation because it provides planet mass, crucial to interpreting atmospheric measurements.

Both TPF-C and TPF-I are needed in order to determine whether a planet is habitable, because they make complementary observations, as follows (assuming an Earth-like planet). Ozone has a very strong infrared (TPF-I) feature, and a weak visible (TPF-C) one, so if ozone is abundant, both can be used to extract the abundance as well as the thermal structure of the atmosphere; if ozone is weak, then only the TPF-I feature will be useable. Water as seen by TPF-C will be near the surface of the planet, but as seen by TPF-I it will be in the upper atmosphere; together both give a more complete picture of the atmosphere. Methane and carbon dioxide and nitrous oxide, in small amounts (as for the present-day Earth) can be detected by TPF-I.

Methane and carbon dioxide, in large amounts (as for the early Earth), can be detected by TPF-C. In addition, for large amounts of methane or carbon dioxide, TPF-I will see mainly the amount in the upper atmosphere, but TPF-C will see mainly the amount in the lower atmosphere, so both are needed for a complete picture. In addition to these “overlap” topics, only TPF-C can measure oxygen, vegetation, and the total column of air (Rayleigh scattering); likewise, only TPF-I can measure the effective temperature.

In short, SIM is needed for planet mass, TPF-C and TPF-I are needed to characterize the atmosphere for habitability, and all three are needed to fully characterize the planet.

Temporal Variability of Composition

Both TPF-C and TPF-I potentially can measure changes in color and the strengths of spectral features as the planet rotates. These changes can tell us the length of day on the planet, and can indicate the presence of large oceans or land masses (with different reflectivities or emissivities, by analogy to Earth). Superposed on this time series of data could be random changes from weather patterns, possibly allowing the degree of variability of weather to be measured.

Owing to the variable air mass above clouds of varying height, the TPF missions can potentially measure variability of composition over time, which we know from our Earth to be an indicator of habitability.

Presence of Water

Both TPF-C and TPF-I have water features in their spectra, so if water vapor is present in the atmosphere, we will be able to measure it. However, habitability requires liquid water on the surface, which in turn requires a solid surface as well as a temperature that permits the liquid state; only with the help of a value of mass from SIM will we be able to know the radius, and when TPF-I is launched, the temperature.

To know whether liquid water is present on the surface of a planet, we need mass data from SIM and spectroscopic water data from TPF-C or TPF-I.

Influence of Other Planets, Orbit Co-planarity

All three missions can detect several planets around a star, within their ranges of sensitivity. Thus, there may be a planet close to the star that SIM can detect, but is hidden from TPF-C. Likewise there may be a distant planet that TPF-C or TPF-I can detect, but has a period that is too long for SIM. For the more subtle issue of whether the planets have orbits in or out of the same plane, SIM will do the best job.

In general, each of the three missions will detect some but not necessarily all of the planets that might be present in a system, so the combination will deliver a complete picture of what planets are present, their masses, their orbits, and how likely they are to influence each other over the age of the system, including co-planarity.

Comets, Asteroids, and Zodiacal Dust

Comets and asteroids have very low masses compared to planets, so will not be detected by SIM; but because they have a large surface area (for their mass) they might be seen collectively, if their numbers are high, by TPF-C in reflected light and TPF-I in thermal emission. Certainly zodiacal dust clouds will be seen easily by both TPF-C and TPF-I.

The combination of TPF-C (visible) and TPF-I (infrared) measurements can tell us about the average albedo and numbers of solid objects (comets and asteroids), as well as ground-up material (exozodiacal dust). With SIM data on planets, the detection of sub-planet material by TPF-C and TPF-I will produce a picture of a planetary system's history and present interactions.

Atmospheric Biomarkers

The simultaneous presence of an oxidized species (like oxygen or ozone) and a reduced species (like methane) is considered to be a sign of non-equilibrium that can indicate indirectly the presence of life on a planet. The presence of a large amount of molecular oxygen, as on the present Earth, may also be an indirect sign of life. In addition, since water is a prerequisite for life, as we consider it here, the presence of liquid water (indicated by water vapor and an appropriate temperature) is needed. Together these spectroscopically detectable species are our best current set of indicators of life on a planet.

These markers will be measured exclusively by TPF-C and TPF-I, but to know that we are observing an Earth-like planet will require SIM data on mass. If we do (or do not) find biomarkers, we will certainly want to know how this is correlated with planet mass.

Surface Biosignatures (Red Edge of Vegetation)

The “red edge” is a property of land plants and trees whereby they are very good reflectors of red light (just beyond the long-wavelength limit of our eyes). This is a useful feature for measuring plant cover on Earth. If exoplanets have developed plant life like that on Earth, and if the planet is bright, has few clouds, and a lot of vegetated land area, then we may use this feature to detect living vegetation.

As for other biomarkers (above), we will want to correlate the presence of vegetation with the planet mass, requiring SIM as well as TPF-C.

Technical Heritage

Each new mission builds on the technological heritage of earlier related missions, and in some cases that inheritance is essential. Examples follow. SIM has developed exquisitely precise methods of measuring the relative locations of optical elements in a train of optics, a technological heritage that will be beneficial to TPF-C and TPF-I. Also, SIM will be the largest interferometer flown in space, thus enabling TPF-I. In addition, since SIM will be the first space instrument to demonstrate aperture synthesis imaging, it paves the way for the next generation of dilute-aperture missions, including TPF-I. Finally, SIM has pioneered methods of accounting for wavefront uncertainties in optical systems, and also in designing technical milestones that the pre-flight development effort must meet in order to pass a series of gates; both of these systems-engineering methods will be valuable to TPF-C and TPF-I as these programs unfold.

Addendum: Calculation of Planet Mass Sensitivity for SIM and TPF-C

Technical details on the calculation of planet mass sensitivity for SIM and TPF-C are summarized here. Corresponding calculations for Kepler and TPF-I will be added in a subsequent white paper.

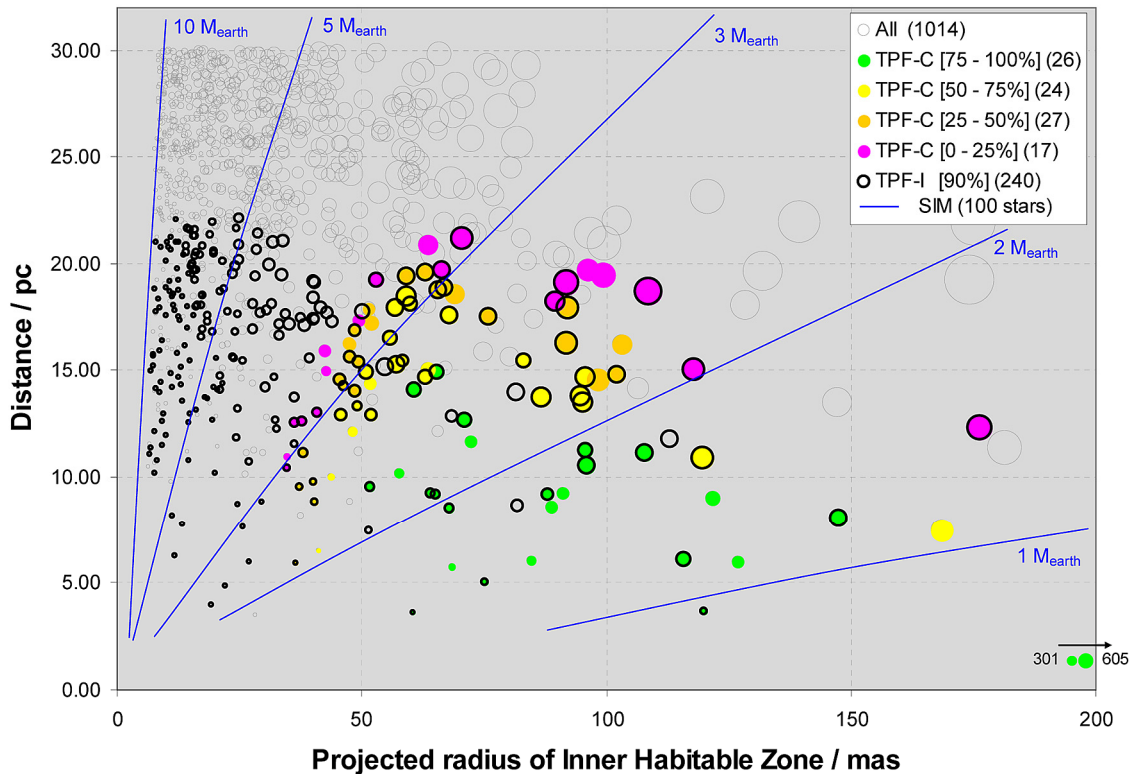


Figure 40. Stars observable by SIM PlanetQuest, TPF-I and TPF-C. (O.P. Lay, JPL)

We define the *minimum mass planet* to be the smallest detectable planet of Earth-like density and albedo and effective temperature. Each mission has a minimum-mass planet that it can detect around each star, given the mission’s specific technique and sensitivity.

For SIM the minimum detectable planet mass is $M(\text{SIM, min.}) = 0.33 M_E D/L^{0.26}$ where M_E is the mass of Earth, D is the distance to the star in parsecs, L is the luminosity of the star in units of solar luminosity (i.e., $L(\text{Sun}) = 1$), and we have assumed SIM’s Level-1 requirement that the minimum detectable amplitude of stellar wobble is 1.0 μas (assuming a false alarm rate of only 1%).

For TPF-C the minimum detectable planet mass is $M(\text{TPF-C, min}) = 0.81 M_E L^{1.50}$, independent of D , where the planet is seen at quadrature (maximum angular separation from its star), and the minimum detectable contrast ratio (planet/star) is 10^{-10} , or 25 magnitudes.

For this analysis, we select the target stars that can be seen by TPF-C according to the following rules:

1. At quadrature the planet must be at least 58 mas distant from its star
2. The star must be brighter than $V = 7$,
3. The star must be closer than 30 pc,
4. The star must have no stellar companion within 10 arcsec, and
5. The star must be on the Main Sequence and of spectral type F, G, K, or M.

We restrict the range of terrestrial planets to the mass range 0.5 to 10 M_E , a theoretically reasonable range because less massive planets will tend to lose their atmospheres quickly (like Mars), and more massive planets will tend to accumulate thick gaseous envelopes (like Jupiter). We also distribute the planets in this range in bins of equal mass size but populated as $1/M$, a rule that is the same as a uniform distribution in log-mass space, as is suggested by observations of more massive planets; however, this distribution is not directly relevant in calculating a minimum detectable mass.

The net result of one such calculation, using the above parameters, is that all these conditions are fulfilled simultaneously for SIM and TPF-C for a joint target list of 139 stars. For each mission, we rank the targets in terms of the minimum-mass terrestrial planet that could be detected around each star. Thus targets with the lowest-mass planet detection limit are first-rank targets. To characterize the kinds of planet masses that could be detected by each mission, we arbitrarily pick the planet in the middle of the top half of each list, i.e., the 25th percentile planet. For SIM this planet has 3.9 Earth masses, and for TPF-C it has 1.1 Earth masses. We expect that for TPF-I the threshold will be even smaller, in the sub-Earth (e.g., Mars) range.

Stars Observable by SIM, TPF-I, and TPF-C

Figure 40 shows the science target stars observable by the SIM PlanetQuest, TPF-I, and TPF-C missions. Each circle represents a star on the TPF target list, selected for the likelihood of harboring habitable planets. There are 1014 in total. The diameter of the circle is proportional to the intrinsic size of the star; the large circles towards the upper right correspond to F stars, the small circles to the lower left are M stars. The projected inner habitable zone (IHZ) corresponds to the radius of the orbit of Venus, scaled appropriately by distance and the luminosity of the star. The Solar System at 10 pc has a projected IHZ of 70 mas; at 15 pc the value is 47 mas.

The colored circles represent those stars for which an Earth-sized planet could be detected in the habitable zone by the TPF-C mission. The color indicates the completeness of the measurement, as indicated in the legend. For example, the yellow symbols show stars for which there is a probability of between 50 and 75% that a given Earth-sized planet in the habitable zone is detected. There are 24 such stars. The completeness diminishes with distance and proximity of the habitable zone to the star.

The circles with a heavy outline denote the 240 stars that can be surveyed for Earth-sized planets in the habitable zone with 90% completeness by the TPF-I mission (linear Dual Bracewell configuration). The inner working angle is significantly less than for TPF-C, allowing access to planets that are closer to the star. Solar shading constraints prevent observation of targets within 45 degrees of the ecliptic poles, which includes approximately one third of the TPF-C targets.

The blue contours represent the planet mass sensitivity of the SIM mission for an Earth-equivalent orbit. The astrometric signature is proportional to the mass of the planet and the projected orbit radius, and inversely proportional to the mass of the parent star. For a star lying on the 3-Earth-mass contour, there is a 50% probability that a given 3-Earth-mass planet will be detected.

Appendix B

Definitions

The definitions given here are for the purpose of clearly specifying the scientific needs of the Navigator Program. Some of these terms are still under debate among scientists. The definitions included here are not meant to be interpreted as a contribution to these debates, rather as a cogent set of terms from which the requirements can be accurately described. However, an attempt has been made to make these definitions fit with current understanding of the science as much as is possible. These definitions originally appeared in the *TPF-C Science and Technology Development Team Report* (Levine *et al.* 2006), and have been updated in a few cases to best represent our current understanding.

Planet

A planet is an object that is gravitationally bound and supported from gravitational collapse by either electron degeneracy pressure or Coulomb pressure, that is in orbit about a star, and that, during its entire history, never sustains any nuclear fusion reactions in its core. Reliance on theoretical models indicates that such objects are less massive than approximately 13 times the mass of Jupiter (M_J) for objects with metallicities close to that of the Sun. Objects with masses between 13 and 75 M_J (known as brown dwarfs) fuse deuterium for a portion of their youth (Sudarsky *et al.* 2003, and references therein). Objects with masses above 75 M_J are known as stars. A lower mass limit to the class of objects called planets has not been convincingly determined. The IAU Working Group on Extrasolar Planets in 2003 defined a “planet” (actually an exoplanet, since Solar System planets were defined by the IAU in 2006) as follows: *Objects with true masses below the limiting mass for thermonuclear fusion of deuterium (currently calculated to be 13 Jupiter masses for objects of solar metallicity) that orbit stars or stellar remnants are “planets” (no matter how they are formed). The minimum mass/size required for an extrasolar object to be considered a planet should be the same as that used in our Solar System.*

Terrestrial Planet

A terrestrial planet is a planet that is primarily supported from gravitational collapse through Coulomb pressure, and that has a surface defined by the radial extent of the liquid or solid interior. Terrestrial planets are often referred to as “rocky planets.” A gaseous atmosphere may exist above the surface, but this is not a defining feature of a terrestrial planet. Theory suggests that most terrestrial planets will have masses less than about 10 times Earth’s mass (M_\oplus), as planets larger than this are likely to capture gas during accretion and develop into giant planets. Terrestrial planets that undergo final accretion after their protostellar nebula has dissipated may, however, achieve larger masses while still remaining “rocky.”

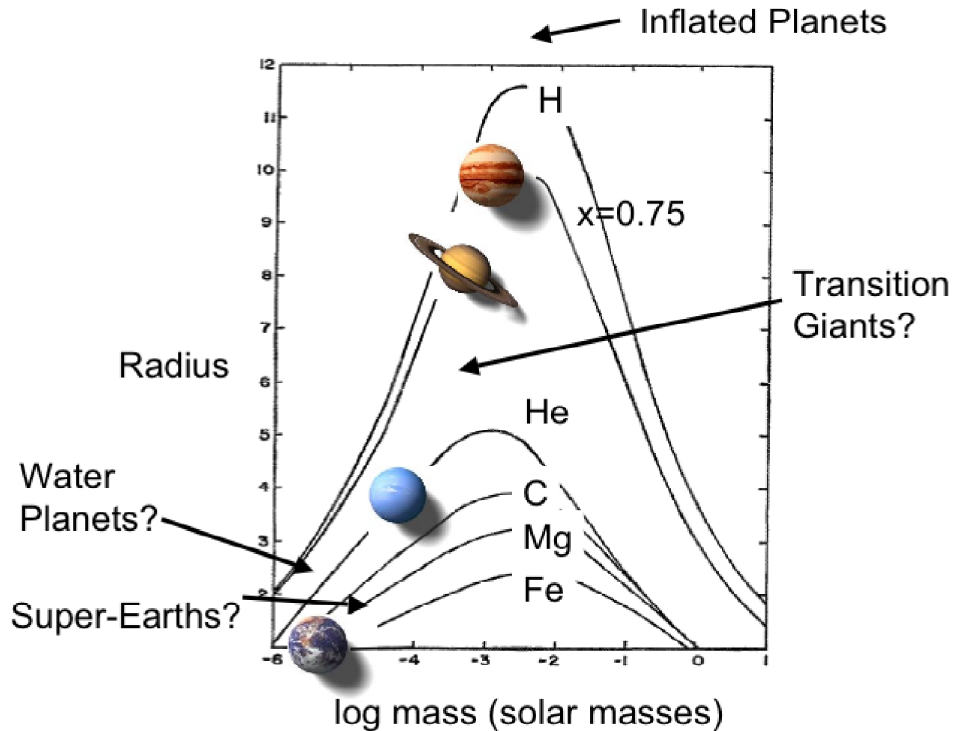


Figure 41. Planetary radius (in units of 10^4 km) as a function of planet mass for zero temperature homogeneous spheres of various compositions (Zapolsky and Salpeter 1969). The masses and radii of Jupiter, Saturn, Uranus, and Neptune are shown.

Potentially Habitable Planet

A potentially habitable planet is a terrestrial planet whose orbital semi-major axis lies within the habitable zone (see definition of Habitable Planet). Its mass must be less than 10 Earth masses to be considered terrestrial and greater than 0.33 Earth masses to be habitable.

Habitable Planet

A habitable planet is a terrestrial planet on whose surface liquid water can exist in steady state. This definition presumes that extraterrestrial life, like Earth life, requires liquid water for its existence. Both the liquid water, and any life that depends on it, must be at the planet's surface in order to be detected remotely. This, in turn, requires the existence of an atmosphere with a surface pressure substantially above the triple point pressure of water, 6.1 mbar, and a mean surface temperature somewhere between 0°C and 374°C (the critical point for water). Planets habitable by Earth-like life must have surface temperatures below $\sim 120^{\circ}\text{C}$. For the purposes of the mission, the lower-mass limit for a habitable planet is set at $1/3 M_{\oplus}$. Smaller objects are unlikely to hold on to their atmospheres effectively and are therefore lower priority targets for TPF-C. For reference, the mass of Mars is $0.1075 M_{\oplus}$, so Mars is not considered to be a habitable planet by this definition.

Caveat: Some planets (or moons) that do not have liquid water at their surfaces may indeed be habitable, or even inhabited. Jupiter’s moon Europa is widely believed to have an ocean of liquid water, or a water-ammonia mixture, beneath its icy surface, in which life could conceivably be present. However, if life is present on Europa, it is *not* detectable from Earth, and it would certainly not be detectable from a planet orbiting a distant star. Mars is another planet where subsurface life is possible. Indeed, measurements of CH₄ in Mars’ atmosphere (Mumma *et al.* 2003; Formisano *et al.* 2004; Krasnopolsky *et al.* 2004) suggest to some researchers that life may be present. The quantities of gas detected, however, are extremely small, and are best detected at very high spectral resolutions ($R \cong 50,000$ for the ground-based measurements) and such sensitivities are unlikely to be accessible to TPF-C. Remote detection of subsurface life on exoplanets is possible in theory, but it will not be considered here.

Earth-Like Planet

A planet is Earth-like if its mass is in the range 0.5 to 2.0 M_{\oplus} , and it is mostly rocky, with some atmosphere and liquid surface water. This definition captures the human point of view that “Earth-like” means a similarity to the present Earth. An Earth-like planet is a subset of habitable planets.

Earth Twin/Solar System Twin

An Earth twin is a planet of exactly one Earth mass and one Earth radius with liquid surface water, Earth’s albedo, and Earth’s atmospheric composition. A Solar System twin is a system of nine planets orbiting a G2V star, *i.e.*, a star like the Sun that is identical in every respect to our own Solar System.

Habitable Zone and Continuously Habitable Zone

The habitable zone, or HZ, is the region around a star in which a planet may maintain liquid water on its surface. Its boundaries are defined empirically, based on the observation that Venus appears to have lost its water some time ago and that Mars appears to have had surface water early in its history. For the present-day Sun, the corresponding HZ limits are 0.75 AU for the inner edge and 1.8 AU for the outer edge. Note that the semi-major axis of Venus is 0.72 AU, and Mars is 1.52 AU, so the Sun’s HZ is shifted outward with respect to these orbits. Briefly, the empirical reason is that water is believed to have existed on both planets at a time in the past when their orbits were about the same as today’s but the Sun was fainter (see next item), and the planets’ atmospheres were different than today’s.

The HZ limits scale as the square root of the star’s luminosity. The total flux incident on the surface of a planet will scale as the square root of the total luminosity of the star, all else being equal. So if the luminosity of the star changes over the star’s lifetime, or if we want to compare a given planet and orbit around different stellar types, then this rule applies.

Caveat. The HZ limits also scale as the square root of the fraction of luminosity that is absorbed, *i.e.*, $(1-A)^{1/2}$ where A is the Bond albedo of the planet. Furthermore, the HZ limits scale as some function of the greenhouse effect, *i.e.*, the amount of heat trapped by infrared-absorbing constituents of the atmosphere.

Both of these effects are empirically included in the limits quoted above, for the cases of ancient Venus and Mars.

The continuously habitable zone, or CHZ, is the region that remains habitable over some substantially finite period of time as a star ages. All main sequence stars brighten with time, and so the HZ moves outward with time. For our own Solar System, the CHZ is usually defined over the entire solar lifetime, ~ 4.6 billion years (Hart 1978).

Caveat: These definitions do *not* preclude the possibility that other planetary bodies (or moons) may support liquid water, and even life, beneath their surfaces. Such life is probably not detectable remotely, however, and thus is not something that can be searched for by *TPF*. Note: The “C” in “CH” should not refer to “circumstellar” because this is redundant for a planet orbiting a star.

Eta_Earth, η_{\oplus}

(Eta_sub_Earth) **Eta_Earth is the fraction of stars that have at least one potentially habitable planet (PHP).** In other words, it is the fraction of stars that have at least one planet within their habitable zone. For this document, this is interpreted to mean the fraction of *observed* stars that have at least one PHP, as it is used to estimate an expectation value for the number of potentially habitable planets, N_{PHP} , that will be found throughout the duration of the mission.

Direct Detection

Direct detection is the observation of photons from a planet obtained by separating the light emitted or reflected by the surface or atmosphere of a planet from that of the star it orbits. The words “direct” and “directly,” when used in reference to “detection,” are specifically meant to distinguish between the TPF-C mission and the vast majority of work in exoplanetary science to date, which has relied on radial velocity measurements of nearby stars or on gravitational microlensing of light from distant stars to reveal the existence of planets. We also use direct detection to include *recording* as much information about the planet light as is technically feasible. More generally, direct detection refers to the ability to distinguish the light emergent from a particular celestial object from that of any other. In the case of TPF-C, the primary issue is that for every 10^{10} photons that arrive from a nearby star, only one is expected from an accompanying Earth-like planet. Detecting these few photons from the planet requires extraordinarily precise instrumentation.

Giant Planet

Giant planets are those with masses substantially greater than terrestrial planets but less than brown dwarfs, e.g., $0.03 M_J < M < 13 M_J$ ($\sim 10 M_{\oplus} < M < \sim 4000 M_{\oplus}$). Our Solar System retains two types of giant planets: gas giants and ice giants. Other types are seen in extrasolar planetary systems. Jupiter and Saturn are *gas giants*, characterized by an extended thick atmosphere composed primarily of hydrogen, with bulk masses of M_J and $0.3 M_J$ respectively (318 and $95 M_{\oplus}$). Their interiors are thought to contain a substantial fraction of metallic hydrogen surrounding a rocky core. Their visible “surfaces” are usually defined to be the cloud-top level at a pressure of roughly 1 bar, typically ammonia clouds for Jupiter and

Saturn. Giant planets younger or more massive than Jupiter will show bright water clouds instead of ammonia clouds. Giants that are even warmer (or young) will be cloud free. *Ice giants*, represented locally by Uranus and Neptune at 0.046 and 0.054 M_J , respectively, (14 and 17 M_{\oplus}) have hydrogen/helium envelopes like gas giants. However, their interiors contain a thick mantle of briny ices, likely water, that surround a rocky core. Their visible cloud-tops (the “surface”) are composed of methane clouds. The term “*Hot Jupiter*” refers to a planet with mass comparable to or greater than that of Jupiter (but less than the deuterium-burning limit of $\sim 13 M_J$) that is located close to its primary star (e.g., within 3 AU). Similarly, a “*Hot Neptune*” will have very different spectral properties than an ice giant in our Solar System. Observing giant planets with a variety of temperatures will elucidate important processes in giant-planet atmospheres and the evolution of these planets over time.

Planetary System Architecture

Planetary system architecture refers to the location, orbits, and masses of the various components of a planetary system, including planets, small bodies, and dust. The presence and properties of giants in a planetary system alter the formation and dynamical evolution of all planets, including any terrestrial planets, residing around their common host star. A systematic determination of giant-planet dynamical properties, including orbital eccentricity and inclination, would permit identification of locations of enhanced formation and islands of stability, not only of other giant planets but also terrestrial planets in multiple-planet systems.

Zodiacal Dust Disk and Exozodiacal Dust Disks

Zodiacal dust is the Solar System cloud of 10–100- μm -diameter silicate grains (e.g., Grun *et al.* 1985) produced by collisions among asteroids and by the outgassing of comets. This sparse disk of zodiacal dust is the most luminous component of the Solar System after the Sun. Zodiacal dust can be seen by the naked eye at a dark site, after sunset or before sunrise, as an upward-pointing triangle of light along the ecliptic plane. **Exozodiacal dust is the extrasolar analog of zodiacal dust.**

Zodiacal Light Flux Unit

We define the zodiacal light flux unit to be 23 visual magnitudes per square arcsec. This is adapted from Bernstein *et al.* (2002) who state: “*At high Galactic and ecliptic latitudes ($>30^\circ$), the sky flux observed from the ground is dominated by terrestrial airglow and zodiacal light (ZL), each with a surface brightness of about 23 AB mag arcsec $^{-2}$.*” Here AB mag is defined as $\text{AB mag} = -2.5 \log F_\nu - 48.6$ where F_ν has units of $\text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1}$. This is the same as Allen’s definition of apparent visual magnitude m_ν , which is $\log f_\lambda(V) = -0.4 m_\nu - 8.43$ at $\lambda = 5500$ Angstrom, where f_λ has units of $\text{erg s}^{-1} \text{cm}^{-2} \text{A}^{-1}$, which converts to $m_\nu = -2.5 \log F_\nu - 48.566$ using $\lambda f_\lambda = \nu F_\nu$. Thus AB mag is the same as apparent visual magnitude, at least in this context.

The zodiacal light flux is a surface brightness. Its numerical value depends on the luminosity of the central star, the line of sight through the disk (angle of observation as well as distance and azimuth from the star), the wavelength (visible light is scattered, infrared light is thermally emitted), the visible scattering function of the dust grains (probably strongly forward scattering), and the size of the dust grains (small grains are

poor radiators and can become super-heated). We provide the corresponding surface brightness for different realizations (orientation, *etc.*) of exozodiacal clouds in Appendix 1.B of the STDT Report (Levine *et al.* 2006). The program ZODIPIC (<http://eud.gsfc.nasa.gov/Marc.Kuchner/home.html>) is an Interactive Data Language (IDL) program that evaluates the zodiacal flux for any given wavelength, star, and disk orientation.

Pericenter Shift

Pericenter shift refers to a disk asymmetry that occurs when the disk contains a planet on an eccentric orbit, and the orbits of the debris particles acquire a forced eccentricity in response to gravitational planetary perturbations. For example, the solar zodiacal cloud contains a pericenter shift of approximately 0.01 AU in response to Jupiter’s eccentricity of 0.048. The offset scales as the eccentricity of the perturbing planet’s orbit. When an asymmetric exozodiacal cloud with pericenter shift is imaged through a coronagraph, the coronagraph may accentuate the disk asymmetry, producing an image with an apparent peak near the inner working angle that can easily be as bright as an Earth-like planet. In order not to confuse a pericenter shift with an extrasolar Earth-like planet, TPF-C and TPF-I should be able to operate under the assumption that exozodiacal clouds commonly have 0.07 AU of pericenter shift, the amount the solar zodiacal cloud would have if Jupiter had an eccentricity of 0.35, the median for exoplanets.

Protoplanetary Debris and Exozodiacal Disks

Circumstellar disks are the host environments of planet formation and signposts of asteroid and comet populations in mature planetary systems. In wavelength-integrated light, disks can be many orders of magnitude brighter than individual exoplanets. Disks are often classified into the following categories:

Young stellar object (“protoplanetary”) disks are disks of gas and dust with radii of several hundred astronomical units, and masses of at least 0.001 to 0.1 M_{\odot} . They are often found around pre-main sequence stars. While the mass of these disks is mostly molecular hydrogen gas, their opacity is dominated by dust grains. They are highly optically thick in scattered light: $\tau \sim 10^2$ – 10^4 . These disks have sufficient mass to form a planetary system like our own, and are considered analogous to the early solar nebula. They are often referred to as protoplanetary disks even if the presence of a forming planet within the disk has not been established observationally. Their central objects are either T Tauri stars or Herbig Ae stars, the pre-main sequence analogs to solar-type and 2–3 M_{sun} stars, respectively. The nearest significant young stellar object populations are located at distances of 120–140 pc; the host stars range in brightness from $V = 6$ to $V = 16$, and the disk angular radii range from 0.3 to 3.0 arcsec. Due to their high optical depths, these disks can be relatively bright in scattered light. Imaging at contrasts of $\sim 10^6$ would enable significant advances over results from HST, and should be straightforward for TPF-C and TPF-I.

Debris disks are dusty products of collisions between remnant planetesimals. One out of every seven main sequence stars possesses an infrared excess indicating the presence of circumstellar dust. Given that the timescales for removal of dust particles via radiation pressure and P-R drag are much less than the ages of these stars, the dust particles cannot be residual material from the protoplanetary disk. Instead, ongoing dust production from asteroid collisions and cometary passages is required. Debris disks are highly tenuous and optically thin; the brightest example, β Pictoris, contains only a few lunar masses of dust.

Little or no gas is found in debris disks, but studies of the gas component are nevertheless important to understanding the dust production and transport mechanisms. The dust in debris disks is usually quite cold, with > 90% of such systems showing detectable infrared excesses only at wavelengths longer than 30 μm . This corresponds to dust in the region 10 to 100 AU from the central star, analogous to the Kuiper Belt region of our own Solar System. Perhaps two hundred debris disks are known from infrared photometry to date, but only 10 relatively high optical depth systems have resolved images at any wavelength. The host stars are located over the distance range 3–100 pc, the host star brightness ranges from $V=0$ to $V=12$, and the disk angular sizes range from ~ 0.3 to 150 arcsec.

Exozodiacal dust disks are tenuous disks of dust, analogous to our Solar System’s zodiacal dust cloud. Exozodiacal dust disks are interesting in their own right as signposts of planets and asteroids, and not just noise for terrestrial planet detection.

Parallel Observations

Parallel observations are those that are made in parallel with planet-searching and characterization. Such observations include studies of exozodiacal dust clouds (under disk science) and deep-field studies of galaxies and quasars (under general astrophysics).

Pointed Observations

Pointed observations refer to science investigations that are carried out separately from planet-searching and characterization, looking at targets that are *not* included in the normal TPF target star list. Examples include observations of dust disks around very young stars and astrophysical observations of non-stellar objects.

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Appendix C

Funded Proposals

SIM Preparatory Science Proposals Funded

SIM Grid Star Verification Program

SIM requires a grid of astrometrically stable reference stars, roughly evenly distributed across the sky, in order to perform wide-angle astrometric measurements. Approximately 1300 K-giant stars are required, no fainter than about $V = 11.5$. The astrometric stability requirement, after fitting for position, parallax, proper motion, and linear acceleration, is $4 \mu\text{s}$ RMS. This amount of jitter is substantially smaller than the expected accuracy of individual SIM measurements of grid stars.

The SIM Grid Star Verification Program is being carried out by three observing groups, selected via the Request For Proposals (RFP) issued by JPL. The RFP was closed in April 2003. Observing began in August 2004, and is expected to continue for approximately 4 years. The following is a brief description of the three programs.

McDonald Observatory 2.1-m Struve Telescope: The University of Texas at Austin maintains the SES, the Sandiford Echelle Spectrograph, which is located at the 2.1-m Otto Struve Telescope at McDonald Observatory. This spectrograph is capable of resolution $R = 60,000$ over the wavelength range 370–1100 nm, with a total spectral coverage in a single exposure range of 100–150 nm. The measurement of radial velocities is achieved by referencing the stellar spectrum to that of an iodine (I_2) spectrum. A new CCD system provides remote guiding (but not autoguiding), and a new set of slit apertures has been installed. The new apertures offer significant improvement to the stability and reflectivity of the slit assembly. Routine observations of the grid star program, conducted via the University of Texas at El Paso under Verne Smith (PI) began in August, 2004. They were assigned 453 bricks for a total of 1377 stars, covering the mid-declinations (+55 deg) down to -20 deg. Thirty-four bricks are shared with the Harvard-Smithsonian Center for Astrophysics (CfA) as a cross-check measure.

La Silla 1.2-m Euler Telescope: The Université de Genève maintains the CORALIE échelle spectrograph and is located at the 1.2-m Leonard Euler Telescope at ESO-La Silla Observatory in Chile. This spectrograph has a resolving power of $R = 50,000$, allowing radial velocity measurements down to a precision of 7 m/s, perfectly suited for detecting extra-solar planets. Its online reduction software computes

radial velocities only several minutes after observations. Like the Advanced Fiber Optic Echelle (AFOE) spectrograph, CORALIE used the double-fiber scrambling method for increased stability. Further stability is maintained by locating the instrument in an isolated and temperature-controlled room. Spectra are referenced using the simultaneous thorium lamp technique. This group was assigned 378 bricks for a total of 1134 stars. As a cross-check measure, the Swiss group shares six bricks with the University of Texas at El Paso. Routine observation of the grid star program, covering the lower declinations (−20 to −90 deg), began in August 2004 by PI Didier Queloz.

Mt. Wilson 100-inch Hooker Telescope: The Harvard–Smithsonian Center for Astrophysics (CfA) maintains the AFOE, the Advanced Fiber Optic Echelle spectrograph. Previously located at the 1.5-m telescope at Whipple Observatory (Tucson, Arizona), it has since been relocated to the Hooker 100-inch telescope atop Mt. Wilson, California. This spectrograph has a maximum resolution of 56,000 over a typical range of 392– 664 nm, spanning 24 orders. The spectrum is recorded on a continuously cooled, thinned, back-illuminated, 2048-by-2048-pixel CCD detector (15 μm pixels). Designed specifically for performing precise radial velocities, the stability of the instrument is achieved by referencing emission lines of a thorium-argon lamp to that of the stellar spectrum, as well as an iodine spectrum. Further instrumental precision is increased by using a double-fiber scrambler, in which a pair of fibers is coupled together using a pair of microlenses, separated by a common focal length. Here, the off-axis angle in the first fiber is mapped into radial position on the face of the second, and then effectively scrambled in the second fiber. The CfA group was assigned 505 bricks for a total of 1515 grid star candidates, covering the northern-most declinations (+55 to +90 deg) and scattered observations in the mid declinations down to −10 deg. The PI at CfA is Sylvain Korzennik. Science-quality data has been collected since June 2005.

SIM Preparatory Science Programs: 1998 and 1999

The NASA Space Interferometry Mission (SIM) Preparatory Science Program was created to support the scientific underpinnings of the SIM mission through investigations that must be undertaken some years in advance of the launch. Of particular need are investigations that will assist in identification of our knowledge about candidate objects for the SIM reference grid. The grid is expected to be composed of astrometrically stable objects with mean separations on the sky of about 4 degrees and no fainter than about 12th magnitude at V-band. Once proper motion and parallax are taken into account, an astrometrically stable object position that is suitable for inclusion in this grid should be reproducible to within 4 μs . This requirement places potentially severe limits on stellar multiplicity, the presence of planetary or other circumstellar systems, and photocenter wandering arising from changes in source structure or appearance. The Preparatory Science Program was focused strongly on the SIM astrometric grid. However, proposals for other long-lead scientific investigations relevant to SIM were also considered.

Table 9. SIM Preparatory Science Programs NRA 98-OSS-07 and NRA 99-OSS-04

PI	Institution	Proposal Title / Year
1998		
Steven Majewski	University of Virginia	A Survey of Distant Halo Giant Stars for the SIM Astrometric Grid and a Deep Probe of the Galactic Halo Structure
David Helfand	Columbia University	A New Bright Quasar Sample for the SIM Extragalactic Frame Tie
Thomas Corbin	U.S. Naval Observatory	USNO Grid Star Selection for SIM
Andreas Quirrenbach	Univ. California, San Diego	Selection of SIM Grid Stars: Astrophysical Criteria and the Role of Astrometric Catalogs and DIVA
Zoran Ninkov	Rochester Institute of Technology	A Sensitive Speckle Search for Duplicity in Candidate Objects for the SIM Reference Grid
Kenneth Johnston	U.S. Naval Observatory	Placing the SIM All-Sky Astrometric Grid onto the ICRS
1999		
Steven Majewski	University of Virginia	The Grid Giant Star Survey for the SIM Astrometric Grid: Northern Hemisphere Extension
Richard Gray	Appalachian State University	Spectral Classification and Determination of the Basic Parameters of Dwarf and Giant Stars earlier than M0 within 40 parsecs
Douglas Geisler	Cerro Tololo Inter-American Observatory	Photometric and Spectroscopic Followup of Grid Giant Star Candidates
Andreas Quirrenbach	Univ. California, San Diego	A Radial Velocity Survey of Candidate SIM Grid Stars
I. Neill Reid	University of Pennsylvania	Meeting the Neighbors: A 2MASS-Based Survey of Stars and Brown Dwarfs Within 20 Parsecs of the Sun

TPF Foundation Science Proposals Funded

Tables 10–16 list the proposals that were funded from 2002 to 2006 for TPF Foundation Science and for related work under the Origins of Solar Systems Program. The tables show the breakdown of topics as described in this document. The name of the Principal Investigator (PI), the institution, and the proposal title are listed. TPF Foundation Science and the Origins of Solar Systems Program are part of NASA’s Research Opportunities in Space and Earth Science NRA, announced every year at the end of January.

Table 10. TPF Foundation Science: Frequency of Terrestrial Planets

PI	Institution	Proposal Title / Year
FY 2002		
Timothy Brown	National Center for Atmospheric Research	Photometric Search for Hot Jupiters Using a Network of Small Telescopes
Paul Butler	Carnegie Institution of Washington	The Magellan Planet Search: Completing the Reconnaissance of Nearby Stars
Laird Close	University of Arizona	The First Nulling and Simultaneous Differential Imaging Survey of Massive Planets and Debris Disks Around Nearby Stars
Drake Deming	NASA Goddard Space Flight Center	Infrared Spectroscopic Detection and Characterization of Extrasolar Planets
Edward Dunham	Lowell Observatory	A Photometric Search for Extrasolar Giant Planets
Geoffrey Marcy	Univ. California, Berkeley	Jupiter Analogs and Rocky Planets Toward 1 m/s Precision
Bohdan Paczynski	Princeton University	Search for Planets with Gravitational Microlensing and Planetary Transits
FY 2003		
Philip Armitage	Univ. of Colorado, Boulder	Population Synthesis of Extrasolar Planetary Systems
David Bennett	University of Notre Dame	A Search for Extra-Solar Planets with Global Microlensing Follow-up Network
Peter Bodenheimer	Univ. California, Santa Cruz	Formation of Giant Planets by Core Accretion – Gas Capture
William Borucki	NASA Ames Research Center	Transit Search for Extrasolar Planets with Vulcan Photometer
Darren DePoy	Ohio State University	Survey for Transiting Extra-Solar-System Planets in Stellar Systems
Douglas Lin	Univ. California, Santa Cruz	The Tidal Interactions Between Short-Period Planets and Their Host Stars
Jack Lissauer	NASA Ames Research Center	Detection and Dynamical Characterization of Extrasolar Planetary Systems
Peter McCullough	Space Telescope Science Inst.	A Photometric Search for Jovian Planets Transiting Very Bright Stars
Keith Noll	Space Telescope Science Inst.	Physical Studies of Brown Dwarfs and Extrasolar Planets
Stanton Peale	Univ. California, Santa Barbara	Dynamics and Origin of Extrasolar Planetary Systems
Steven Pravdo	Jet Propulsion Laboratory	Stellar Planet Survey

Table 11. TPF Foundation Science: Frequency of Terrestrial Planets (continued)

PI	Institution	Proposal Title / Year
FY 2004		
Fred Adams	University of Michigan	Estimating the Fraction of Solar Systems with Habitable Planets: Effects of Companions on Dynamical Stability and Formation
John Chambers	Carnegie Institution of Washington	Terrestrial Planet Formation Around Nearby Stars
William Cochran	University of Texas at Austin	Determination of eta-Earth from Ground-Based RV Observations of M Stars
Gregory Laughlin	University of California, Santa Cruz	A Consortium-Based Theoretical Evaluation of the Frequency of Habitable Planets
Harold Levison	Southwest Research Institute	Extra-Solar Terrestrial Planet Formation
John Monnier	University of Michigan	Detecting and Characterizing “Hot Jupiters” with Optical Interferometry: Differential Phase and Precision Closure Phases
Robert Noyes	Smithsonian Astrophysical Observatory	Spreading the Net: A Network of Small Automated Telescopes for Detecting Transiting Extrasolar Planets
Stuart Weidenschilling	Planetary Science Institute	Accretion of Terrestrial Planets in Extrasolar Planetary Systems
Harold Yorke	Jet Propulsion Laboratory	Formation and Evolution of Planetary Systems: Predicting the Frequency of Earth-like Planets Around Nearby Stars
Darren DePoy	Ohio State University	Planet Search from High Magnification Microlensing Events
Darren DePoy	Ohio State University	KELT All-Northern Sky Transit Survey: A Survey of Bright Stars for Transiting Planets
Shrinivas Kulkarni	California Institute of Technology	Extrasolar Planets in Binary Stellar Systems
Gregory Laughlin	University of California, Santa Cruz	Detection of Intermediate-Period Transiting Planets Through the Coordination of Follow-up Observations of Known Doppler-Wobble Planet-bearing Stars
Steven Saar	Harvard-Smithsonian Center for Astrophysics	Improving Doppler Searches for Exoplanets by Reducing Activity-related Radial Velocity Noise
Guillermo Torres	Smithsonian Astrophysical Observatory	Spectroscopic Follow-up of OGLE Candidate Transiting Extrasolar Planets

Table 12. TPF Foundation Science: Frequency of Terrestrial Planets (continued)

PI	Institution	Proposal Title / Year
FY 2005		
Craig Agnor	Univ. California, Santa Cruz	Collisional and Dynamical Evolution of Planets
Timothy Brown	National Center for Atmospheric Research	A Coordinated Photometric Search for Transiting Extrasolar Planets
David Charbonneau	California Institute of Technology	The Sleuth Automated Wide-field Survey for Transiting Extrasolar Planets
Laird Close	University of Arizona	Simultaneous Differential Imaging Surveys for the Detection of Young Nearby Extra-Solar Planets
William Cochran	University of Texas at Austin	A Radial Velocity Search for Extrasolar Planets Using the Hobby-Eberly Telescope
Edward Dunham	Lowell Observatory	Photometric Search for Extrasolar Giant Planets
Debra Fischer	San Francisco State University	N2K: A Search for Short-Period Planets Orbiting Metal-rich Stars
George Gatewood	University of Pittsburgh	A Search for Jovian Planets Around the Nearest Low Luminosity Stars
Lynne Hillenbrand	California Institute of Technology	Young Solar Analogs: Companion Search via Adaptive Optics Imaging and Photospheric Characterization via Echelle Spectroscopy
Shrinivas Kulkarni	California Institute of Technology	PHASES: Palomar High-Precision Astrometric Exoplanet Search
Renu Malhotra	University of Arizona	Dynamical Processes in Planetary Systems
Geoffrey Marcy	Univ. California, Berkeley	Jupiter Analogs and Sub-Saturn Mass Planets: Toward 1 m/s Precision
FY 2006		
John Gizis	University of Delaware	Observations of a Brown Dwarf Planetary System
Matthew Holman	Smithsonian Astrophys. Obs.	High-Precision Photometry of OGLE Transiting Extrasolar planets
Matthew Kenworthy	Steward Observatory	Detecting Exo-Jupiters Through Focal Plane Wavefront Sensing
Bohdan Paczynski	Princeton University	The OGLE Search for Planets
Peter McCullough	Space Telescope Science Inst.	The XO Planet Finding Program
Geoffrey Marcy	Univ. California, Berkeley	Search for Rocky Planets Around Nearby Stars

Table 13. TPF Foundation Science: Exozodiacal Dust

PI	Institution	Proposal Title
FY 2002		
Chris Koresko	California Institute of Technology	High-Resolution Infrared Imaging of Disks and Companions in Binary T Tauri Systems
FY 2003		
Thangasamy Velusamy	Jet Propulsion Laboratory	Dynamical Modeling and Detectability of Debris Disk Structure – Laying the Groundwork for TPF
Steve Vogt	Univ. California, Berkeley	Precision Radial Velocity Spectrometer for the UCO/Lick Observatory Automated Planet Finder Facility
FY 2004		
Philip Hinz	University of Arizona	High-Dynamic Range Thermal Infrared Surveys for Zodiacal Disks and Giant Planets Around TPF-Candidate Stars
Alice Quillen	University of Rochester	Detection of Outer Extra Solar Planets and Characterization of Disk Properties from Circumstellar Gas and Dust Morphology
FY 2005		
John Monnier	University of Michigan	Infrared Interferometry of Young Stellar Objects: First Images of the Hot Inner Disk Using Closure-Phase Arrays
William Ward	Southwest Research Institute	Disk Planet Interactions and Particle Belts

Table 14. TPF Foundation Science: Target Stars

PI	Institution	Proposal Title
FY 2003		
Verne Smith	Univ. Texas, El Paso	High-Resolution Spectroscopy to Probe the Links Between Stellar Chemistry and Planetary Formation
FY 2004		
John Stauffer	SIRTF Science Center, Caltech	StARS — The Stellar Archival and Retrieval System for TPF Foundation Science
Karen Willacy	Jet Propulsion Laboratory	Prebiotic Chemistry in Planet-Forming Regions
FY 2005		
Ben Oppenheimer	American Museum of Natural History	The Lyot Project: Surveying TPF target Stars and Pioneering TPF Techniques
FY 2006		
Brian Mason	U.S. Naval Observatory	Duplicity, Binarity, and Masses for TPF Target Stars

Table 15. TPF Foundation Science: Signs of Life

PI	Institution	Proposal Title
FY 2002		
Linda Brown	Jet Propulsion Laboratory	Laboratory Spectroscopy of Hot Methane Bands
FY 2003		
Andrew Friedson	Jet Propulsion Laboratory	Extrasolar Giant Planets: Photochemical Production of Haze and Trace Species and Implications for their Spectra
Joseph Harrington	Cornell University	The Composition and Temperature of the Transiting Extrasolar Planet HD 209458b
Mark Marley	NASA Ames Research Center	Photochemical and Cloud Processes in the Atmospheres of Extrasolar Giant Planets
Sara Seager	Carnegie Institution of Washington	Global Atmospheric and Interior Modeling of Extrasolar Giant Planets
Wesley Traub	Smithsonian Astrophys. Obs.	Spectra and Biomarkers of Extrasolar Planets
Edwin Turner	Princeton University	Toward Realistic Photometric Scattering and Emission Models of Extrasolar Terrestrial Planets
FY 2004		
Travis Barman	Wichita State University	Modeling the Global Atmospheric Properties and Phase Dependent Spectroscopy of Extrasolar Giant Planets
James Cho	Carnegie Institution of Washington	The Global Surface Temperature and Cloud Cover of Extrasolar Terrestrial Planets: Implications for Habitability and Detectability
Martin Cohen	Univ. of California, Berkeley	Absolute FUV-FIR Spectral Energy Distributions: a Tool for Selecting TPF Target Stars and Sharper Criteria for Habitability
Eric Gaidos	University of Hawaii at Manoa	Observable Signatures of Extreme Seasonality on Earth-like Planets with High Orbital Eccentricity or Obliquity
Thomas Hearty	Jet Propulsion Laboratory	Whole Earth Spectra with the Atmospheric Infrared Sounder
FY 2005		
James Kasting	Pennsylvania State University	Predicting the Observability of Ozone and other Biomarker Gases on Planets Around M Stars

Table 16. TPF Foundation Science: Other Related Topics

PI	Institution	Proposal Title
FY 2003		
Don Winget	University of Texas at Austin	Project Dying Stars: a Search for Extrasolar Planets Around White Dwarf Stars
Alexander Wolszczan	Pennsylvania State University	Planets Around Neutron Stars

Appendix D

Acronyms

AAAC	Astronomy and Astrophysics Advisory Committee
AAG	Astronomy and Astrophysics Research Grants (NSF)
AAPF	(NSF) Astronomy and Astrophysics Postdoctoral Fellowships
AAT	Anglo-Australian Observatory
ACS	Advanced Camera for Surveys
ADONIS	ADaptive Optics Near Infrared System
ADP	Astrophysics Data Program (NASA Research Announcement)
AFOE	Advanced Fiber Optic Echelle spectrograph
AGN	Active Galactic Nuclei
ALMA	Atacama Large Millimeter Array
AO	Adaptive Optics
APL	Applied Physics Laboratory
APRA	Astronomy and Physics Research and Analysis (NASA Research Announcement)
ASO	Astronomical Search for Origins
ASP	Arizona Search for Planets
ASTID	Astrobiology Science and Technology Instrument Development and Mission Concept Studies (NASA Research Announcement)
ATI	Advanced Technologies and Instrumentation
ATLO	Assembly, Test, and Launch Operations
AU	Astronomical Unit
BEST	Berlin Exoplanet Search Telescope
CCD	Charge-Coupled Device
CCDM	Catalog of Components of Double and Multiple (stars)
CDM	Cold Dark Matter
CfA	Harvard–Smithsonian Center for Astrophysics
CHZ	Continuously Habitable Zone
CMOS	Complementary Metal Oxide Silicon
CNES	Centre National d’Etudes Spatiales
COROT	Convection Rotation and planetary Transits
CSA	Canadian Space Agency
CTIO	Cerro Tololo Inter-American Observatory
Decl	Declination
EIRB	External Independent Readiness Review Board

EPIcS	Extrasolar Planet Interferometric Survey
EROS	Expérience pour la Recherche d'Objets Sombres
ESA	European Space Agency
ESO	European Southern Observatory
ESTEC	European Space Research and Technology Centre
EXB	Exobiology (NASA Research Announcement)
ExNPS	Exploration of Neighboring Planetary Systems
FFI	Formation Flying Interferometer
FGS	Fine Guidance Sensor
FOV	Field of View
FUSE	Far Ultraviolet Spectroscopic Explorer
GENIE	Ground-Based European Nulling Interferometer Experiment
GEST	Galactic Exoplanet Survey Telescope
GOES	Geosynchronous Orbiting Environmental Satellite
GOME	Global Ozone Monitoring Experiment (ESA)
GSFC	Goddard Space Flight Center
HARPS	High Accuracy Radial velocity Planet Searcher
HD	Henry Draper Catalog
HET	Hobby-Eberly Telescope
HIRES	HIgh-Resolution Echelle Spectrograph
HQ	Headquarters
HST	Hubble Space Telescope
HZ	Habitable Zone
IAC	Instituto de Astrofísica de Canarias
ICRF	International Celestial Reference Frame
IDL	Interactive Data Language (programming language)
IGM	Inter-Galactic Medium
IHZ	Inner Habitable Zone
INT	Isaac Newton Telescope
IPAC	Infrared Processing and Analysis Center
IR	InfraRed
IRAC	Infrared Array Camera
IRAS	Infrared Astronomical Satellite
IRS	InfraRed Spectrograph
IRSA	InfraRed Science Archive
IRT	Independent Review Team
ISM	Inter-Stellar Medium
IUE	International Ultraviolet Explorer
JCMT	James Clerk Maxwell Telescope
JDEM	Joint Dark Energy Mission
JHU	Johns Hopkins University
JKT	Jacobus Kapteyn Telescope
JPL	Jet Propulsion Laboratory
JWST	James Webb Space Telescope
KBO	Kuiper-Belt object
KI	Keck Interferometer

LBT	Large Binocular Telescope
LBTI	Large Binocular Telescope Interferometer
LF	Life Finder
LMC	Large Magellanic Cloud
LSST	Large Synoptic Survey Telescope
LTSA	Long-Term Space Astrophysics theory program (NASA Research Announcement)
MACHO	MAssive Compact-Halo Objects
mas	milli-arcsecond
ME	Mass of Earth
MJ	Mass of Jupiter
μ as	microarcsecond
MicroFUN	Microlensing Follow-Up Network
MIPS	Multiband Imaging Photometer for Spitzer
MIRI	Mid-Infrared Instrument
MIT	Massachusetts Institute of Technology
MOA	Microlensing Observations in Astrophysics (survey)
MOST	Microvariability and Oscillations of Stars (project)
MPS	Microlensing Planet Search
MSC	Michelson Science Center
MSTO	Main-Sequence Turn-Off
NAI	National Astrobiology Institute
NASA	National Aeronautics and Space Administration
NEAR	Near-Earth Asteroid Rendezvous (probe)
NED	NASA/Infrared Processing and Analysis Center Extragalactic Database
NGST	Next Generation Space Telescope (see also JWST)
NICI	Near Infrared Coronagraphic Imager
NICMOS	Near Infrared Camera and Multi-Object Spectrometer
NIR	Near InfraRed
NIRCAM	Near Infrared Camera
NOAO	National Optical Astronomy Observatory
NRA	NASA Research Announcement
NRAO	National Radio Astronomy Observatory
NRC	National Research Council
NStars	Nearby Stars Database Project
OGLE	Optical Gravitational Lensing Experiment
OHP	Observatoire de Haute Provence
OSS	Office of Space Science
OSS	Origins of Solar System (NASA Research Announcement)
PAL	Present Atmospheric Level
PATM	Planetary Atmospheres (NASA Research Announcement)
pc	parsec
PGG	Planetary Geophysics and Geology
PHP	Potentially Habitable Planet
PI	Principal Investigator
PLANET	Probing Lensing Anomalies NETwork
PMS	Pre-Main-Sequence

POP	Program Operating Plan
ppmv	parts per million by volume
PRIMA	Phase-Referenced Imaging and Micro-arcsecond Astrometry at the VLTI
PSPC	Position Sensitive Photon Counters (for ROSAT)
PSF	Point Spread Function
R&A	Research & Analysis (program)
RA	Right Ascension
RFP	Request for Proposals
RMS	Root Mean-Square
Robonet	(global network of the world's biggest robotic telescopes)
ROSAT	Röntgen Satellite (NASA)
ROSES	Research Opportunities in Space and Earth Sciences
RV	Radial Velocity
SAFIR	Single Aperture Far-Infrared Observatory
SCI	Structurally Connected Interferometer
SCIAMACHY	Scanning Imaging Absorption Spectrometer for Atmospheric Chartography/Chemistry (ESA)
SED	Spectral Energy Distribution
SES	Sandiford Echelle Spectrograph
SIRTF	Space Infrared Telescope Facility (renamed Spitzer Space Telescope)
SIM	Space Interferometry Mission
SIMBAD	Astronomical database (Centre de Données Astronomiques de Strasbourg)
SOFIA	Stratospheric Observatory For Infrared Astronomy
SOHO	SOlar and Heliospheric Observatory
Spitzer	Spitzer Space Telescope (formerly SIRTF)
STARE	Stellar Astrophysics & Research on Exoplanets
StARS	Stellar Archival and Retrieval System
STDT	(TPF-C) Science and Technology Definition Team
STEPS	Single Telescope Extrasolar Planet Survey
STEPSS	Survey for Transiting Extrasolar Planets in Stellar Systems
STIS	Space Telescope Imaging Spectrograph
STScI	Space Telescope Science Institute
SWG	Science Working Group
TEP	Transits of Extrasolar Planets (network)
TES	Thermal Emission Spectrometer
TPF	Terrestrial Planet Finder
TPF-C	Terrestrial Planet Finder Coronagraph
TPF/FS	Terrestrial Planet Finder / Foundation Science (NASA Research Announcement)
TPF-I	Terrestrial Planet Finder Interferometer
UC	University of California
UCLES	University College London Echelle Spectrograph
UCO	University of California Observatories
URL	Universal Resource Locator
USNO	United States Naval Observatory
UV	Ultraviolet
VLT	Very Large Telescope

VLTI	Very Large Telescope Interferometer
VRE	Vegetation Red Edge
WMKO	W.M. Keck Observatory
XMM	X-ray Multi-Mirror mission

Appendix E

Contributors and Credits

This book was written by the exoplanet science and astrophysics communities, and its purpose is to serve those communities. In May 2006 about 70 scientists from these communities gathered in an open meeting, the Navigator Science Forum, to review and debate the status of the field, and to formulate the draft version of this book. Their input is the heart of this book. The editors have done what editors do: assemble, smooth, bind, and add where needed. The results of the forum meeting itself and several stages of the book were reviewed by two science panels, the Navigator Program Science Liaison Group and the External Independent Readiness Board. The editors are grateful to these reviewers and to the individuals who were responsible for specific chapters, as listed below.

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The editors are grateful for additional help from Roger Carlson at JPL publications. This text has its origins in the document, *Preparatory Science for the Terrestrial Planet Finder* (JPL Publications 04-14, 2004) and further credit is due to the contributors mentioned therein.

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